Theoretical Perspective on Electromagnetic Radiation at RHIC

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1.) Intro: EM Spectral Function + Fate of Resonances

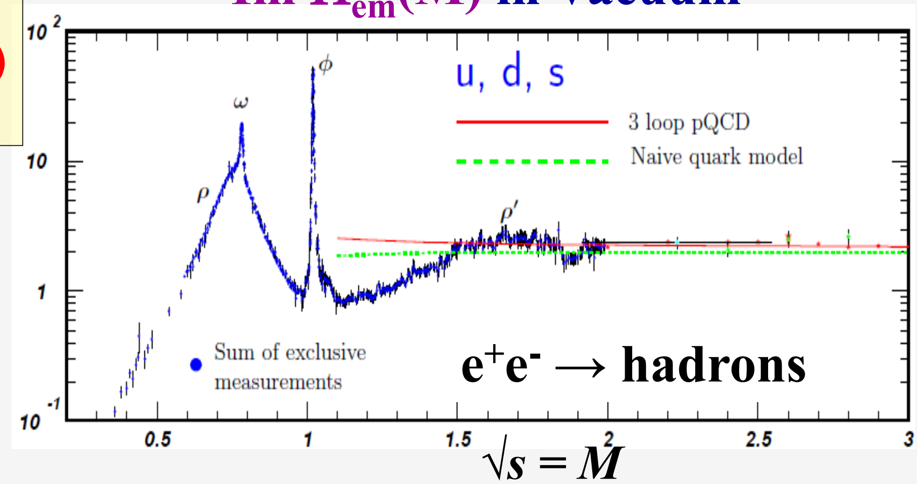
$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T)\ \mathit{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

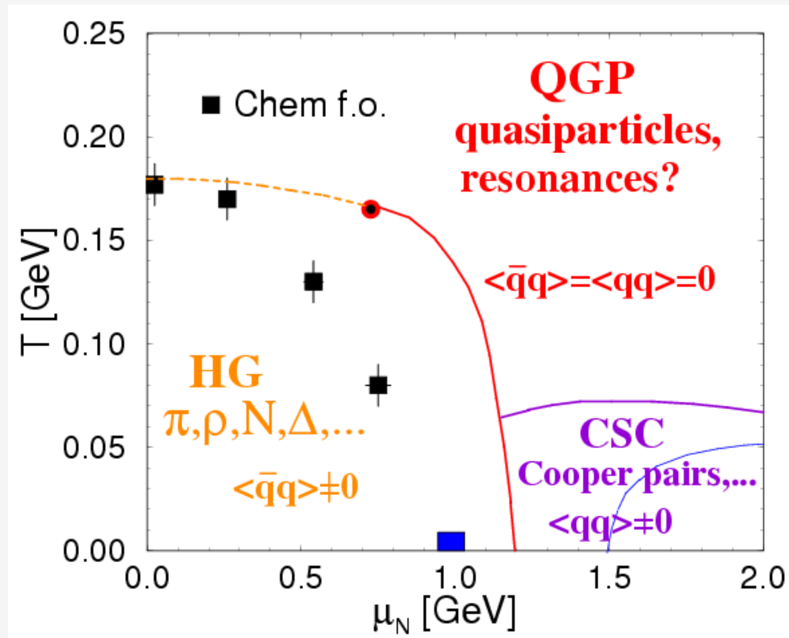
- **Electromagn. spectral function**
  - $\sqrt{s} < 2$ **GeV** : non-perturbative
  - $\sqrt{s} > 2$ **GeV** : perturbative ("dual")

- **Vector resonances "prototypes"**
  - representative for bulk hadrons: neither Goldstone nor heavy flavor

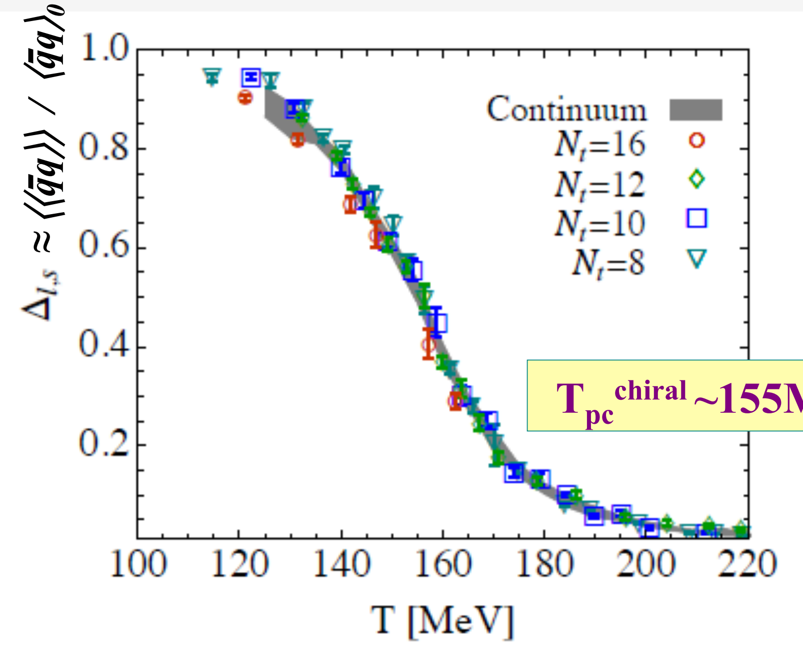
- **Modifications of resonances**
  ↔ phase structure:
  - hadron gas → Quark-Gluon Plasma
  - realization of transition?

Im Π_{em}(M) in Vacuum

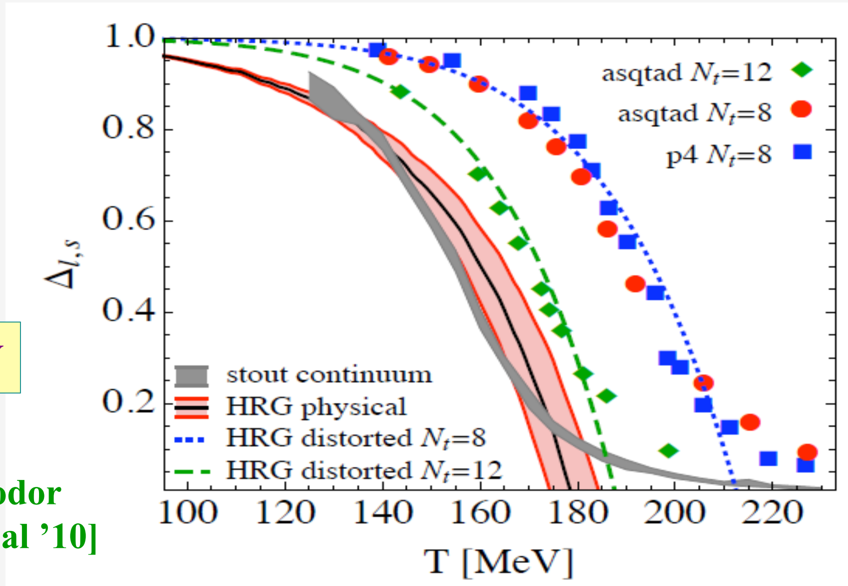




1.2 Phase Transition(s) in Lattice QCD



T_{pc}^{chiral} ~155MeV



[Fodor et al '10]

- cross-over(s) ↔ smooth EM emission rates across T_{pc}
- chiral restoration in "hadronic phase"? (low-mass dileptons!)
- hadron resonance gas $\dfrac{\langle\langle\bar{q}q\rangle\rangle(T,\mu_B)}{\langle\bar{q}q\rangle} = 1 - \sum_h \dfrac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2} \simeq 1 - \dfrac{T^2}{8 f_\pi^2} - \dfrac{1}{3}\dfrac{\varrho_N}{\varrho_0} - \cdots$

Outline

2.) Chiral Symmetry Breaking in Vacuum

- Hadron Spectrum + Sum Rules

3.) Axial-/Vector Spectral Function in Medium

- Hadronic Theory
- QGP + Lattice QCD
- Assessing Chiral Restoration

4.) EM Probes at RHIC

- In-Medium Spectrometer
- Thermal Photons
- P_t Spectra + Collectivity

5.) Conclusions

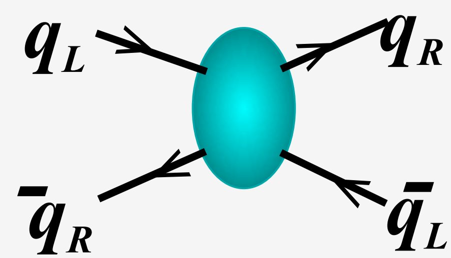
2.1 Chiral Symmetry + QCD Vacuum

$\mathcal{L}_{\rm QCD}(m_{u,d} \approx 0)$: flavor + "chiral" (left/right) invariant

"Higgs" Mechanism in Strong Interactions:

• $\bar{q}q$ attraction $\Rightarrow$ condensate fills QCD vacuum!

$$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \approx -5\, fm^{-3}$$



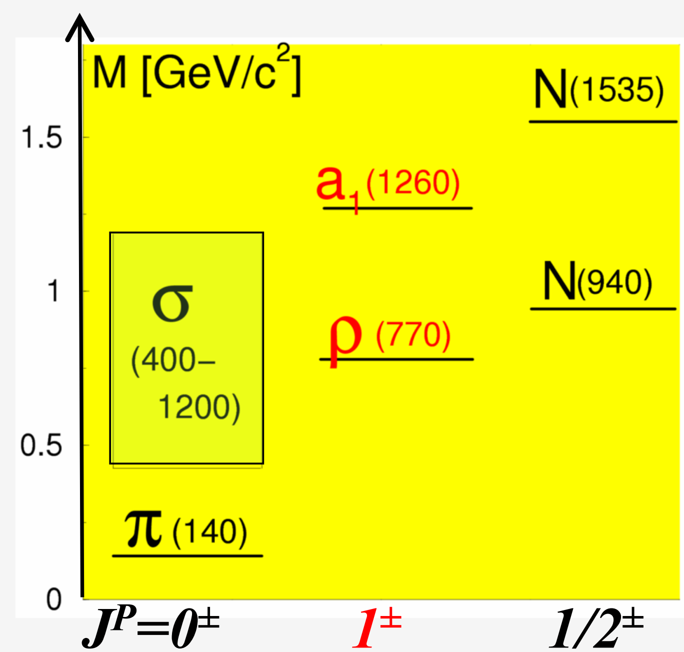
Spontaneous Chiral Symmetry Breaking

Profound Consequences:

• effective quark mass: $m_q^* \propto \langle 0|\bar{q}q|0\rangle$
↔ **mass generation!**

• near-massless Goldstone bosons $\pi^{0,\pm}$

• "chiral partners" split: $\Delta M \approx 0.5\mathrm{GeV}$



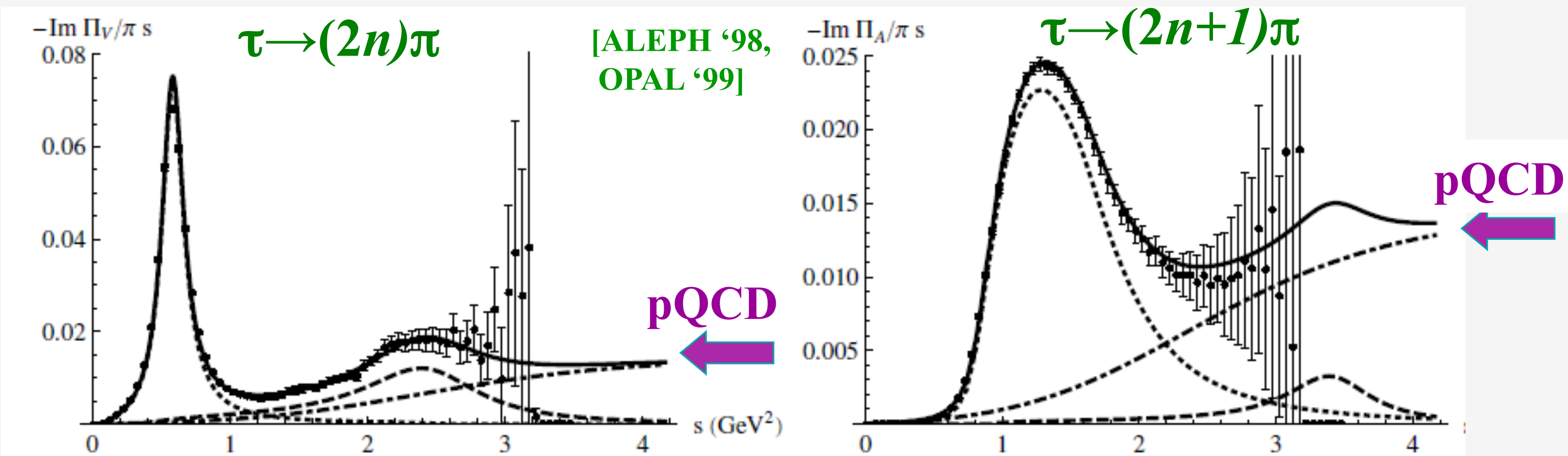
2.2 Chiral (Weinberg) Sum Rules

- Quantify chiral symmetry breaking via observable spectral functions
- Vector **(ρ) -** Axialvector **(a_1)** spectral splitting

$$\boxed{I_n = -\int \frac{ds}{\pi} s^n \left(Im\Pi_V - Im\Pi_A \right)}$$

[Weinberg '67, Das et al '67]

$$I_{-2} = \frac{1}{3} f_\pi^2 r_\pi^2 - F_A , \qquad I_{-1} = f_\pi^2 ,$$
$$I_0 = -2m_q \langle 0 | \bar{q}q | 0 \rangle , \quad I_1 = c\alpha_s \langle 0 | (\bar{q}q)^2 | 0 \rangle$$

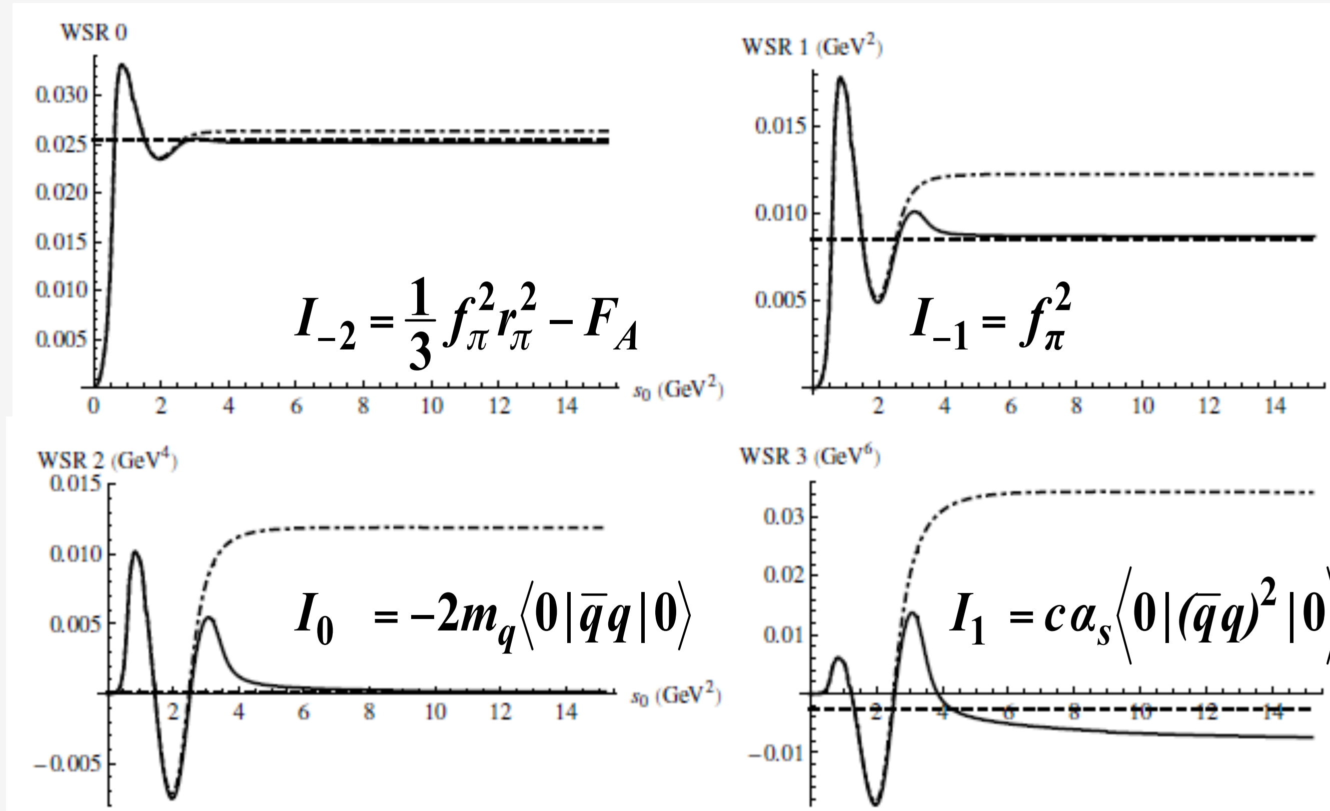


- Key features of updated "fit": [Hohler+RR '12]

  ρ + $\mathbf{a_1}$ resonance, excited states (ρ'+ $\mathbf{a_1}$'), universal continuum (pQCD!)

2.2.2 Evaluation of Chiral Sum Rules in Vacuum

- **pion decay constants**
- **chiral quark condensates**



- vector-axialvector splitting (one of the) cleanest observable of spontaneous chiral symmetry breaking
- promising starting point to search for chiral restoration

2.3 QCD Sum Rules: ρ and a_1 in Vacuum

• dispersion relation:

$$\int_0^\infty \frac{ds}{s} \frac{Im\Pi_\alpha(s)}{Q^2+s} = \frac{\Pi_\alpha(Q^2)}{Q^2}$$

[Shifman,Vainshtein+Zakharov '79]

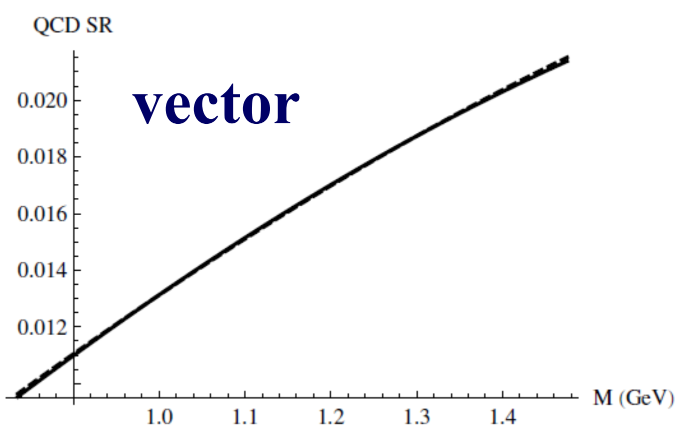
• ***lhs:*** hadronic spectral fct.

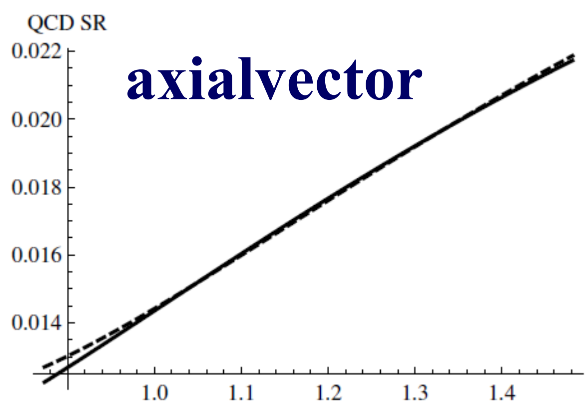
• ***rhs:*** operator product expansion

$$\frac{1}{M^2}\int_0^\infty ds \frac{\rho_V(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) + \frac{m_q\langle\bar{q}q\rangle}{M^4} + \frac{1}{24M^4}\langle\frac{\alpha_s}{\pi}G^2_{\mu\nu}\rangle - \frac{56\pi\alpha_s}{81M^6}\langle\mathcal{O}_4^V\rangle\ldots$$

$$\frac{1}{M^2}\int_0^\infty ds \frac{\bar{\rho}_A(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) + \frac{m_q\langle\bar{q}q\rangle}{M^4} + \frac{1}{24M^4}\langle\frac{\alpha_s}{\pi}G^2_{\mu\nu}\rangle + \frac{88\pi\alpha_s}{81M^6}\langle\mathcal{O}_4^A\rangle\ldots$$

• 4-quark + gluon **condensate** dominant





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3.) Axial-/Vector Spectral Function in Medium

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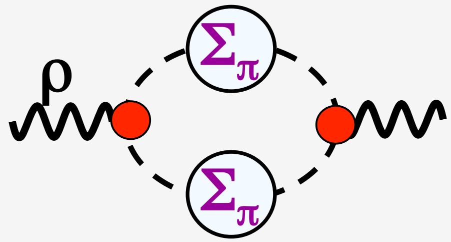
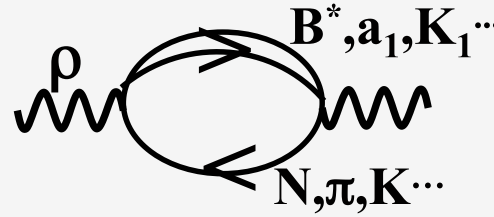
3.1 Vector Mesons in Hadronic Matter

[Chanfray et al, Herrmann et al, Asakawa et al, RR et al, Koch et al, Klingl et al, Post et al, Eletsky et al, Harada et al …]

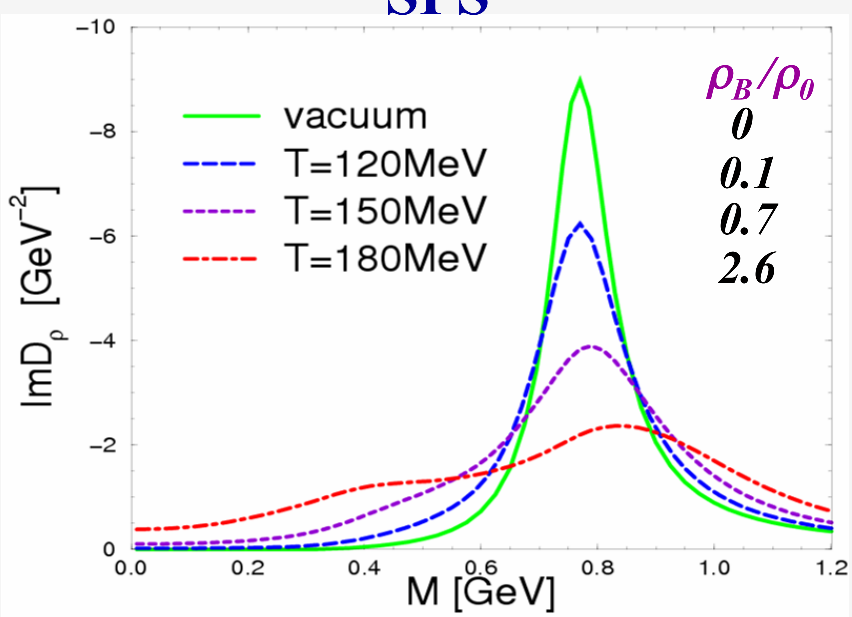
ρ-Propagator: $D_\rho(M,q;\mu_B,T) = [M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]^{-1}$

Selfenergies: $\Sigma_{\rho\pi\pi} =$ 

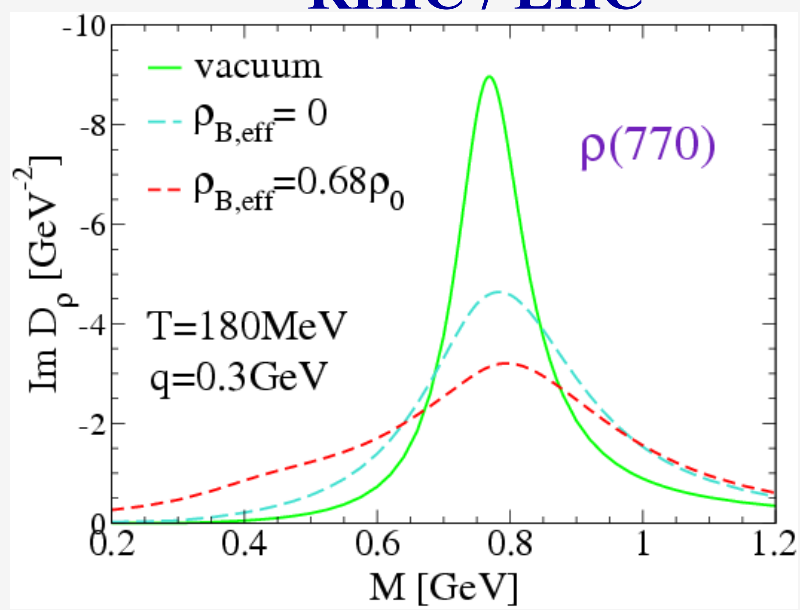
$\Sigma_{\rho B,\rho M} =$ 

Constraints: decays: **B,M→ ρN, ρπ, ... ;** scattering: **πN→ρN, γA, …**

SPS

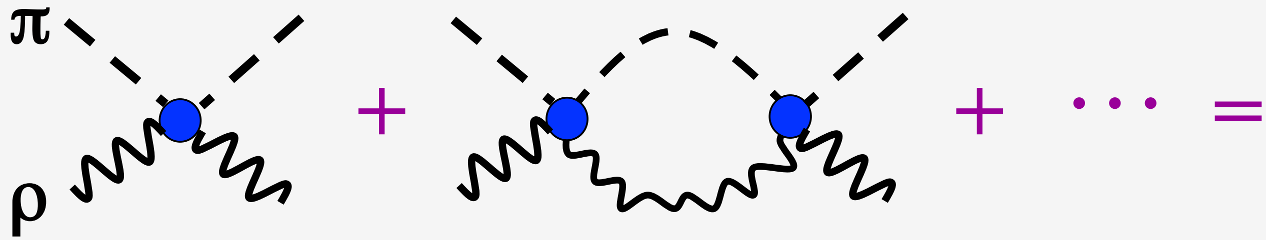


RHIC / LHC



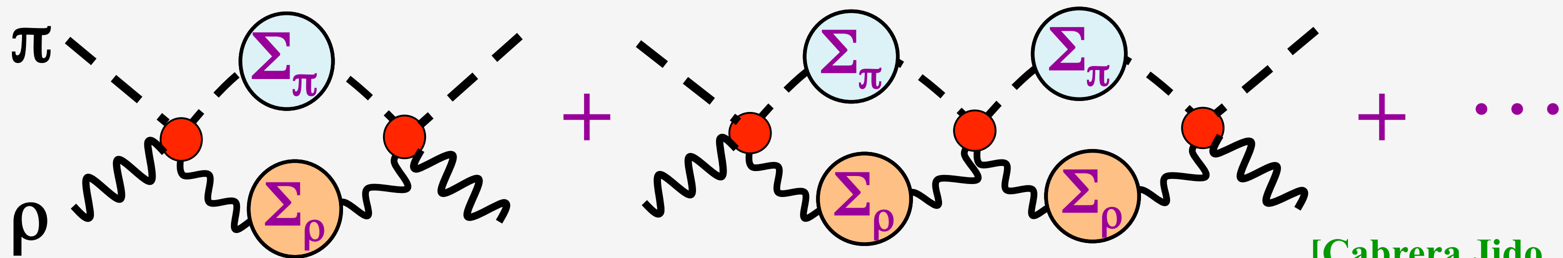
3.2 Axialvector in Nucl. Matter: Dynamical $a_1(1260)$

Vacuum:

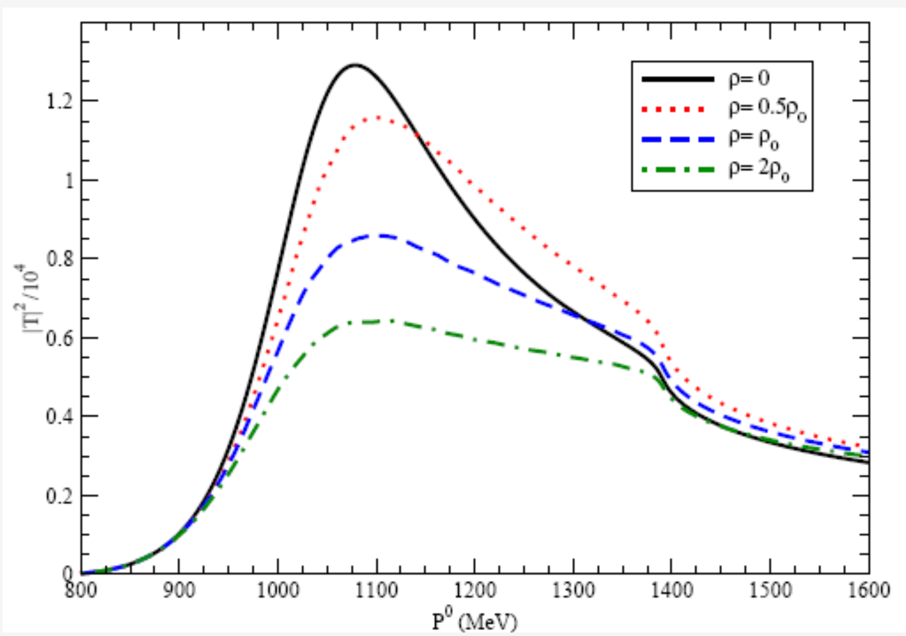


a_1 **resonance**

In Medium:



[Cabrera,Jido, Roca+RR '09]



- in-medium $\pi + \rho$ propagators
- broadening of π-ρ scatt. Amplitude
- pion decay constant in medium:

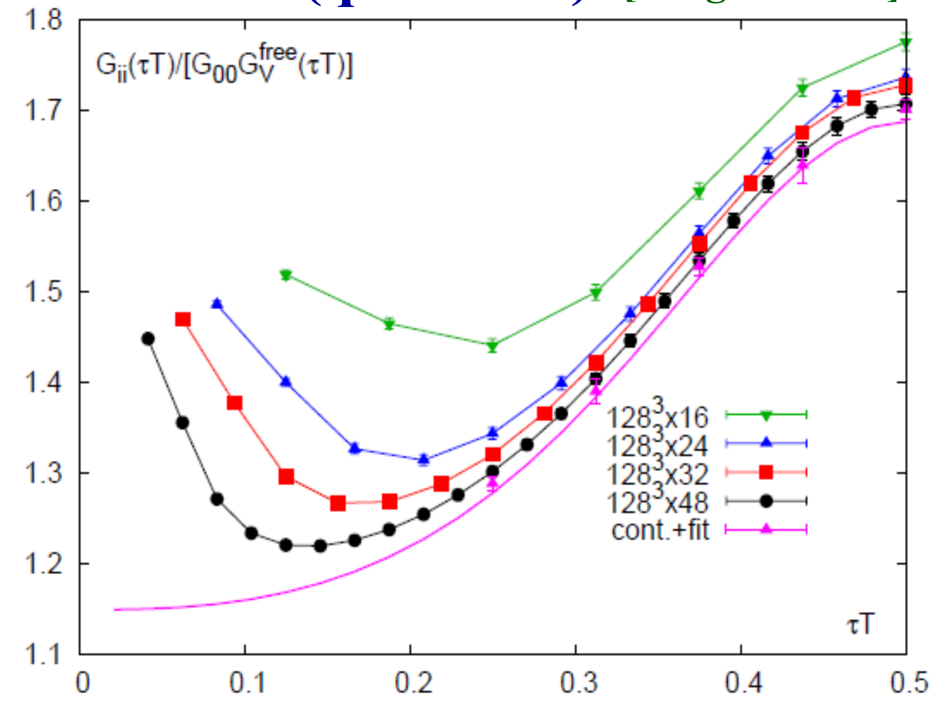
ρ/ρ_0	present work (π-selfenergy A)	present work (π-selfenergy B)
0	93	93
1/2	100-108	91-101
1	65-86	66-93

3.3 Vector Correlator in Thermal Lattice QCD

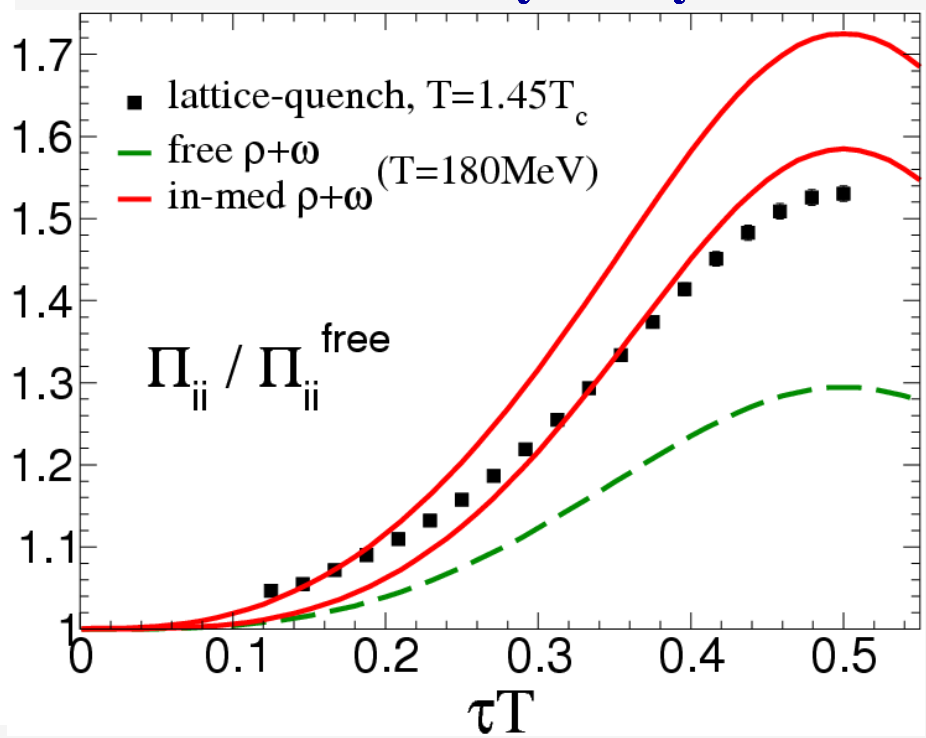
- **Euclidean Correlation fct.**

$$\Pi_{em}(\tau,q;T)=\int_0^\infty \frac{dq_0}{2\pi}\,\rho_{em}(q_0,q;T)\,\frac{\cosh[q_0(\tau-1/2T)]}{\sinh[q_0/2T]}$$

Lattice (quenched) [Ding et al '10]

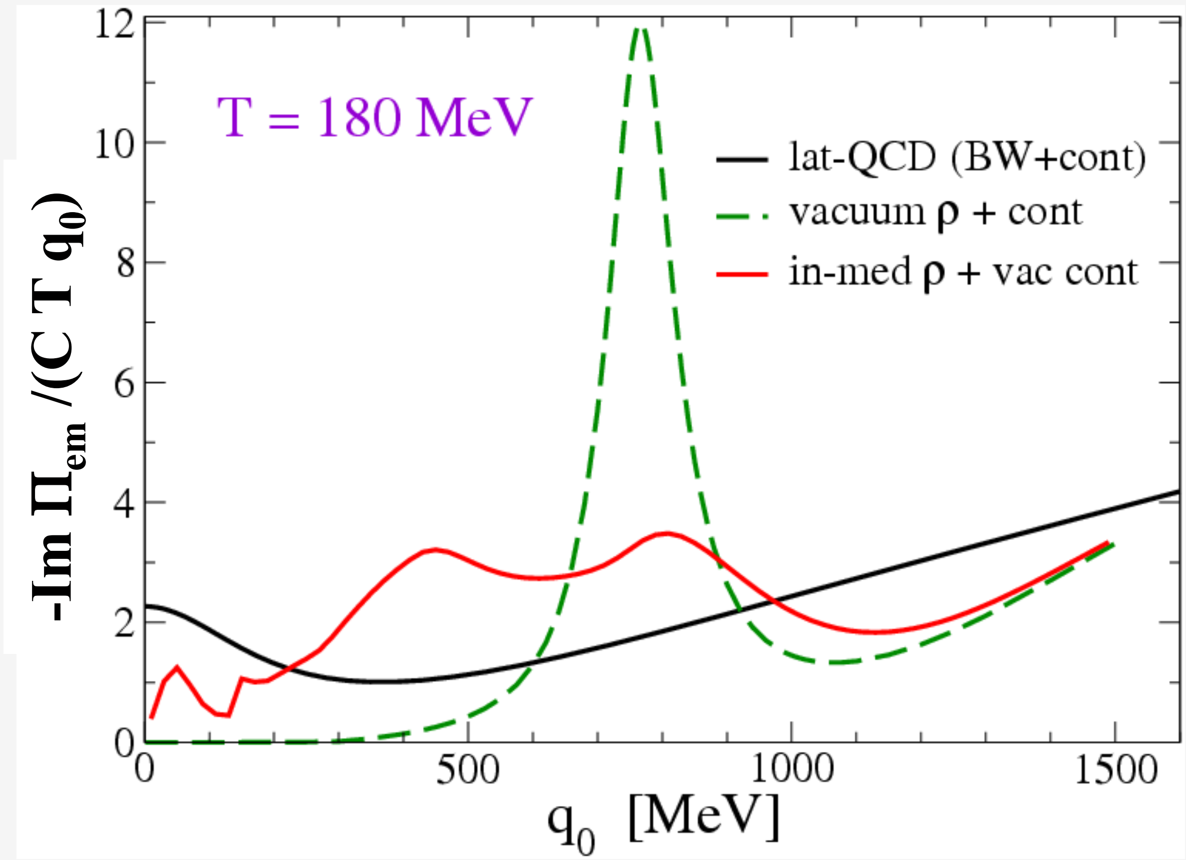


Hadronic Many-Body [RR '02]



- **"Parton-Hadron Duality" of lattice and in-medium hadronic?!**

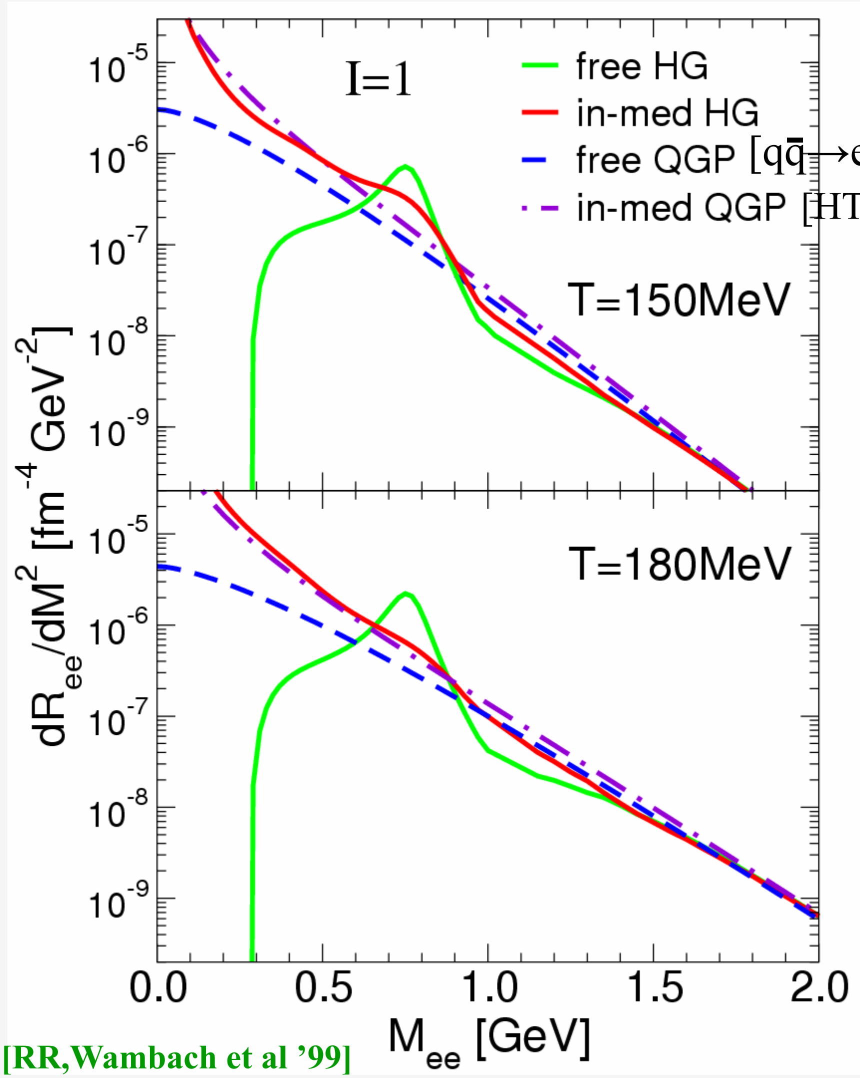
3.3.2 Back to Spectral Function



• **suggests approach to chiral restoration + deconfinement**

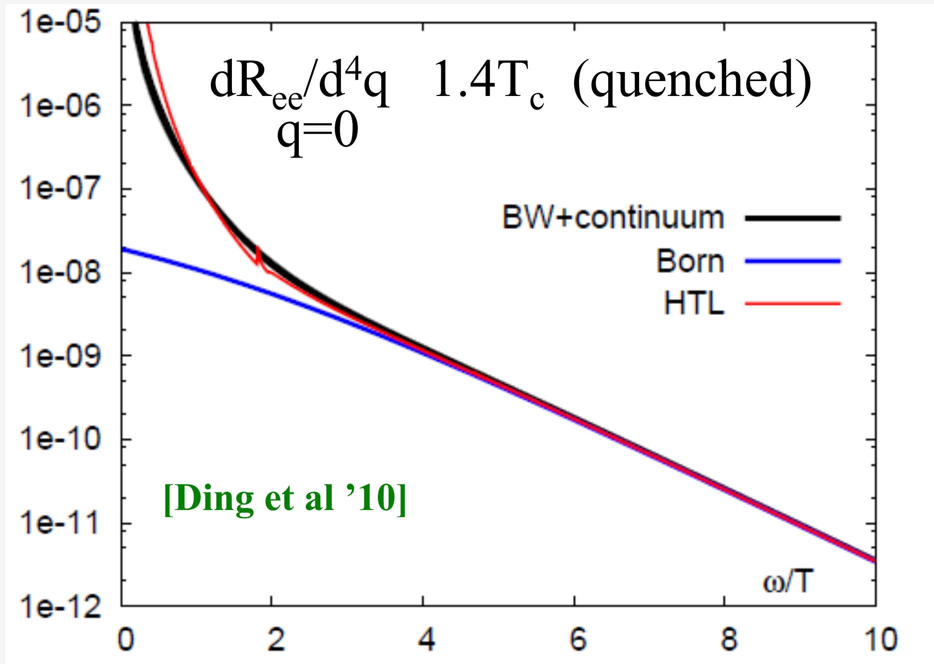
3.4 Dilepton Rates: Hadronic - Lattice - Perturbative

$dR_{ee}/dM^2 \sim \int d^3q\ f^B(q_0;T)\ \mathrm{Im}\,\Pi_V$



[RR,Wambach et al '99]

- **3-fold "degeneracy" toward ~T_c**
- **Quark-Hadron Duality** at all **M** ?!
  (⇔ degenerate **axialvector** SF)



[Ding et al '10]

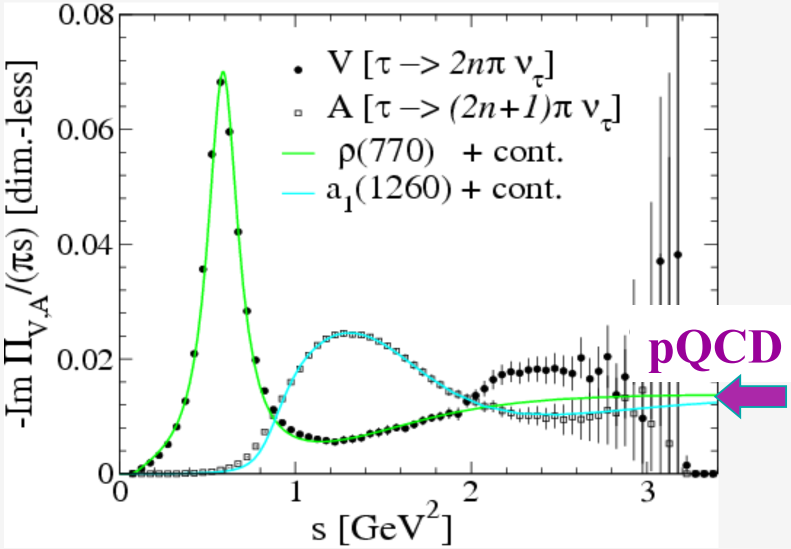
3.5 Summary: Criteria for Chiral Restoration

- Vector (ρ) – Axialvector (a_1) degenerate

$$\boxed{I_n = -\int \frac{ds}{\pi} s^n \left(Im\Pi_V - Im\Pi_A \right)}$$

[Weinberg '67, Das et al '67]

$$I_{-1} = f_\pi^2 , \quad I_0 = 0 , \quad I_1 = c\alpha_s \left\langle (\bar{q}q)^2 \right\rangle$$



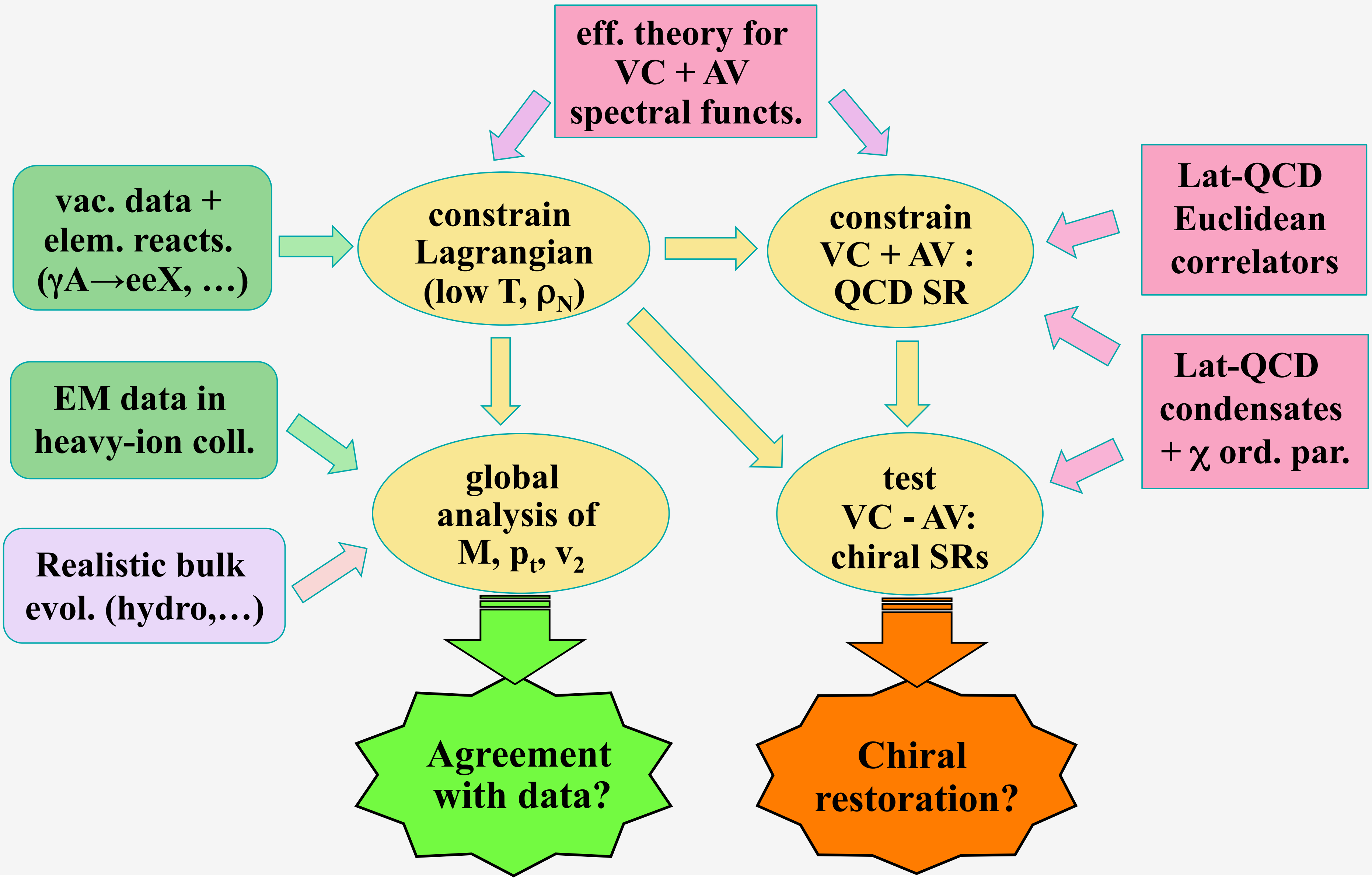
- QCD sum rules:

  medium modifications ↔ vanishing of condensates

- Agreement with thermal lattice-QCD

- Approach to perturbative rate (QGP)

3.6 Strategies to Test For Chiral Restoration



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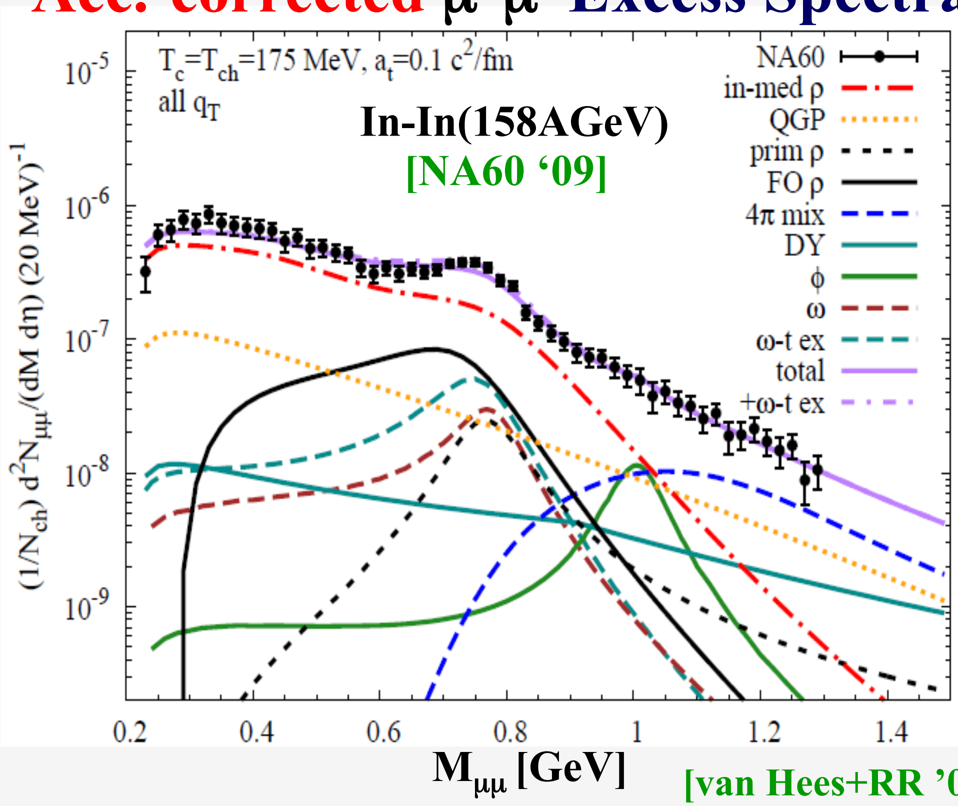
4.1 Dilepton Rates vs. Exp.: NA60 "Spectrometer"

• Evolve rates over fireball expansion:

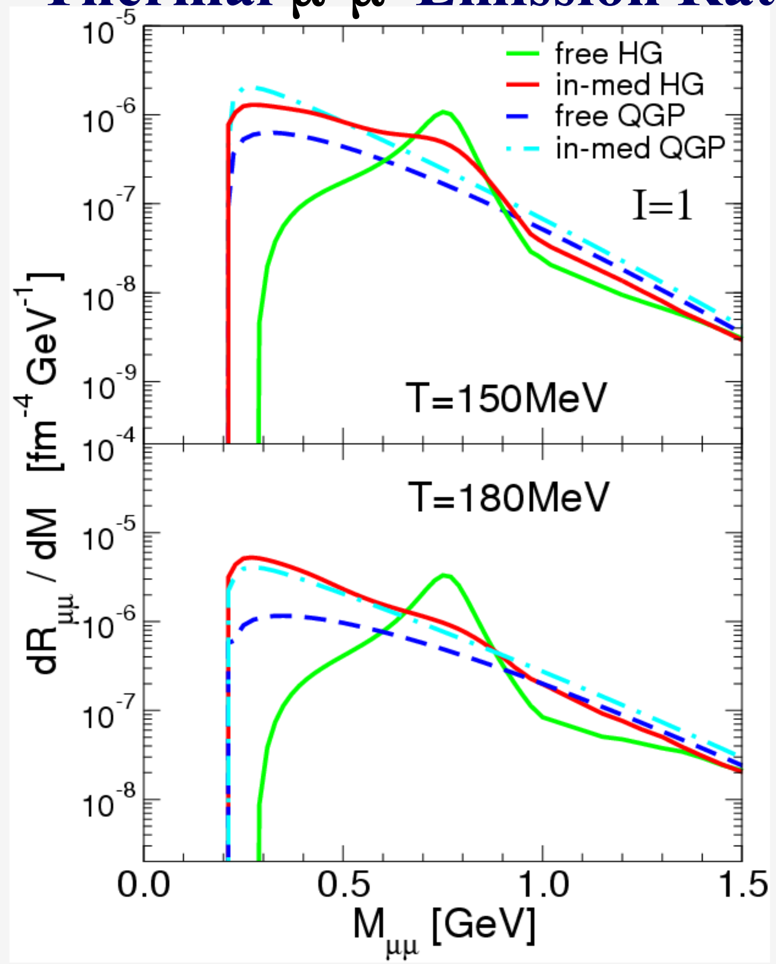
$$\frac{dN^{therm}_{\mu\mu}}{dM} = \int_{\tau_0}^{\tau_{fo}} d\tau\, V_{FB}(\tau) \int \frac{M\, d^3q}{q_0} \frac{dR^{therm}_{\mu\mu}}{d^4q}$$

Acc.-corrected $\mu^+\mu^-$ Excess Spectra



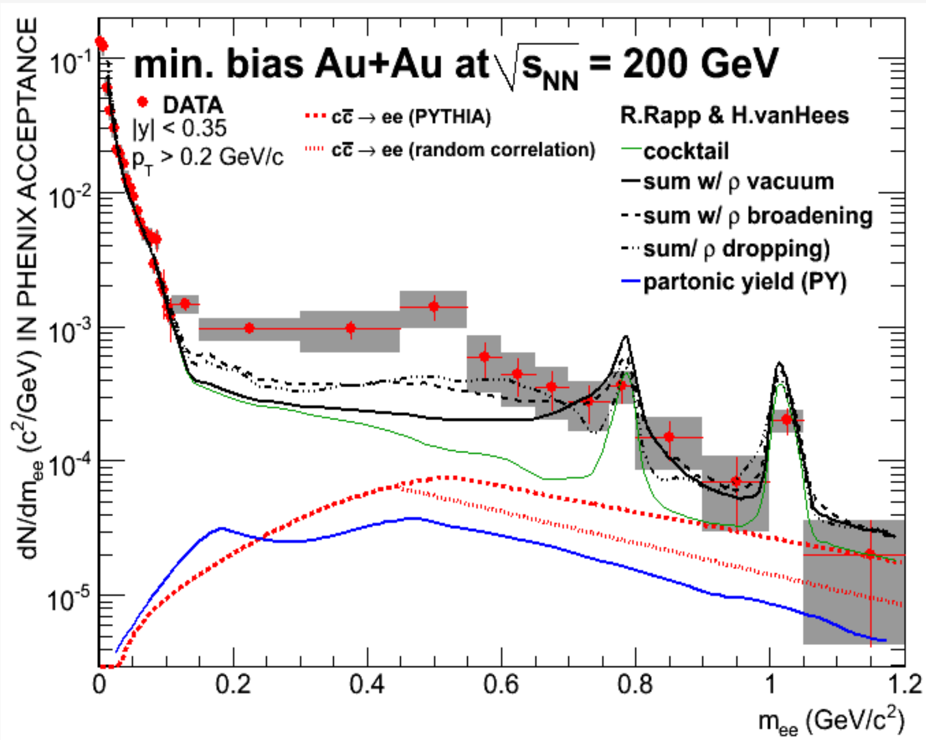
[van Hees+RR '08]

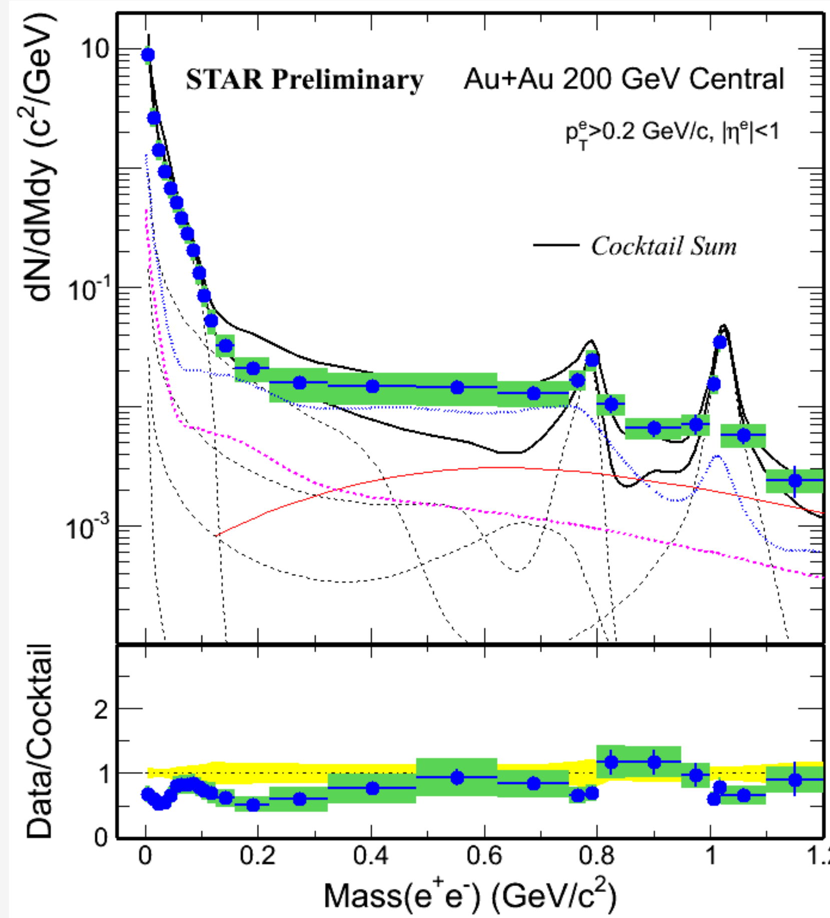
Thermal $\mu^+\mu^-$ Emission Rate



• invariant-mass spectrum directly reflects thermal emission rate!

4.2 Low-Mass e^+e^- at RHIC: PHENIX vs. STAR



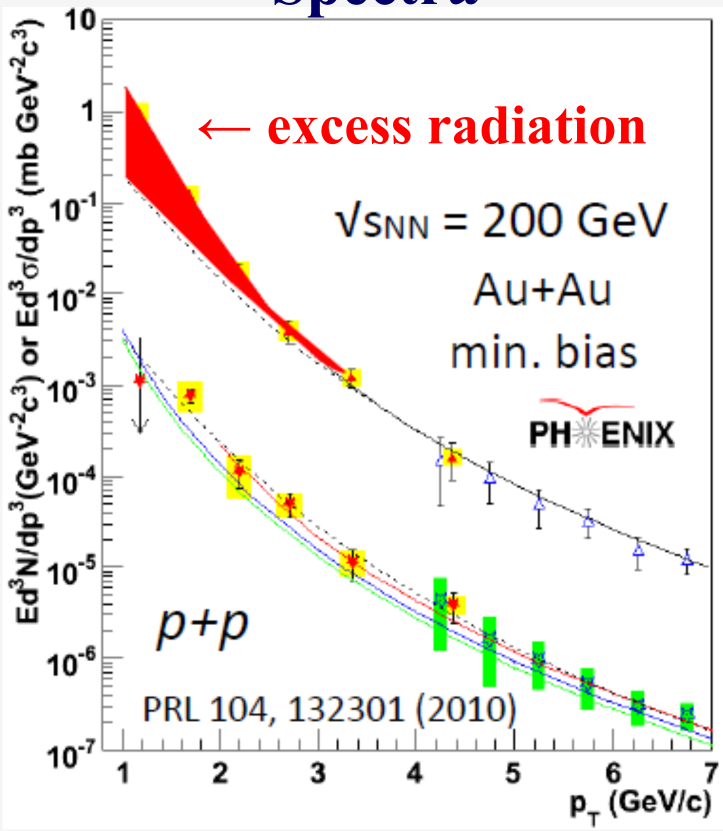


- "large" enhancement not accounted for by theory
- cannot be filled by QGP radiation…

- (very) low-mass region overpredicted… (**SPS**?!)

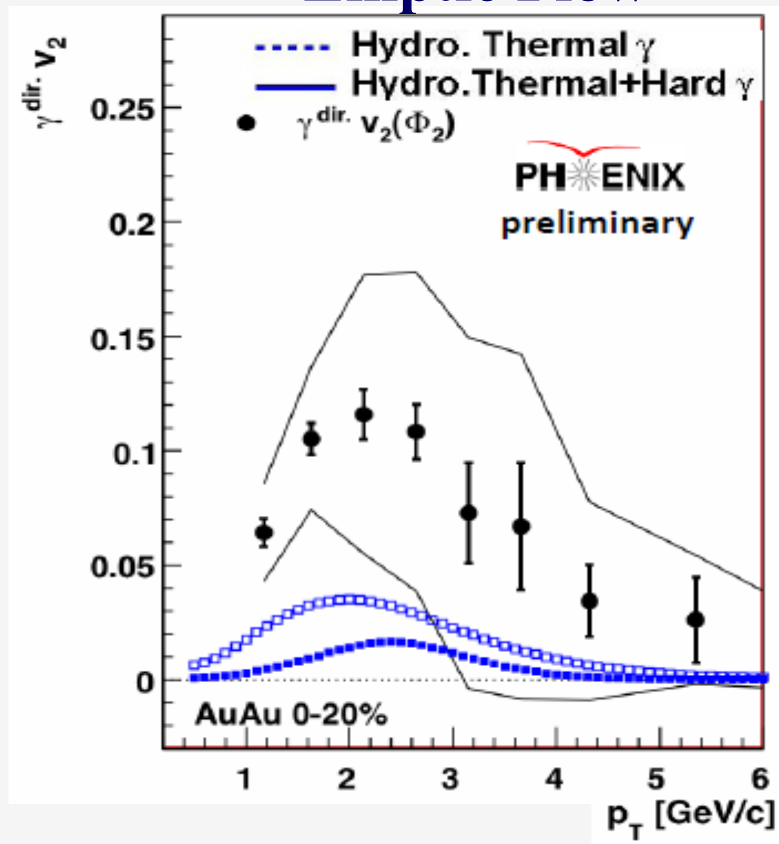
4.3 Direct Photons at RHIC

Spectra



- T_{eff}^{excess} = (220±25) MeV
- QGP radiation?
- radial flow?

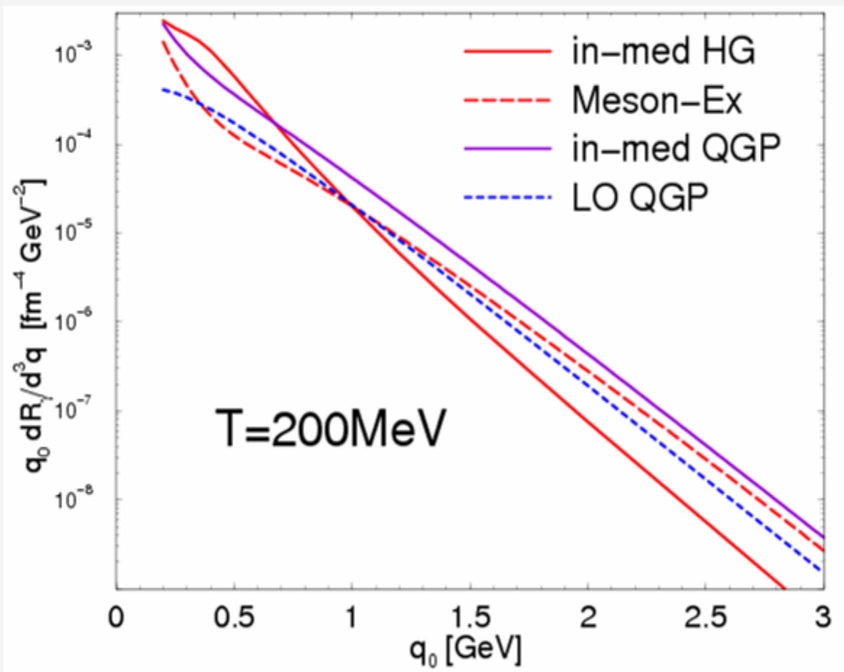
Elliptic Flow



- $v_2^{\gamma,dir}$ comparable to pions!
- under-predicted by early QGP emission [Holopainen et al ’11,…]

4.3.2 Revisit Ingredients

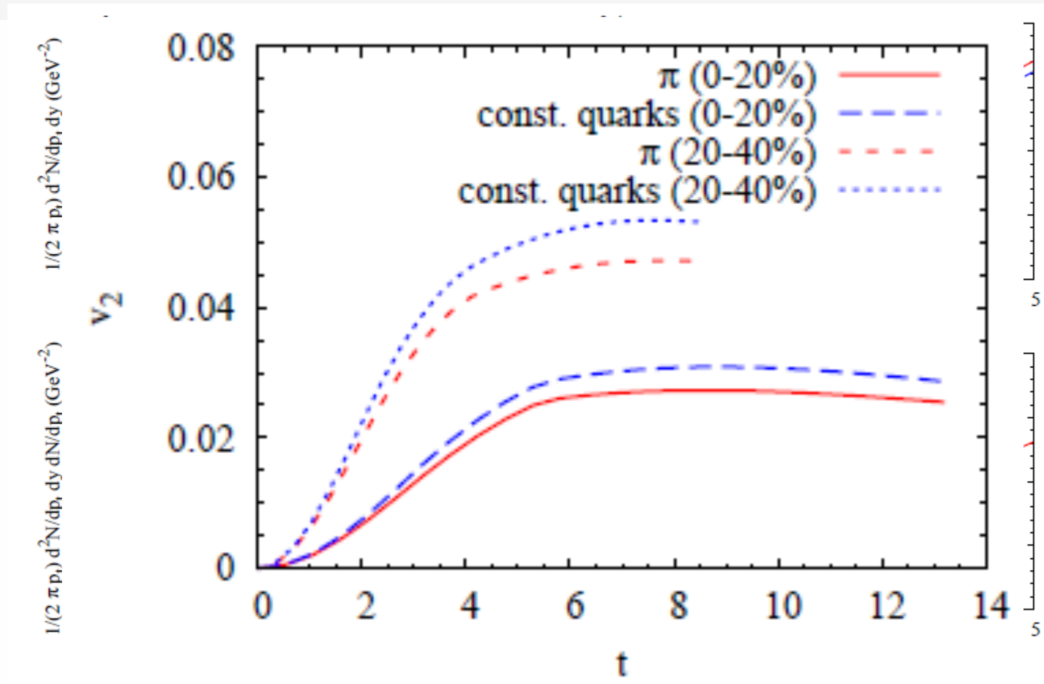
Emission Rates



- Hadron - QGP continuity!
- conservative estimates…

[Turbide et al '04]

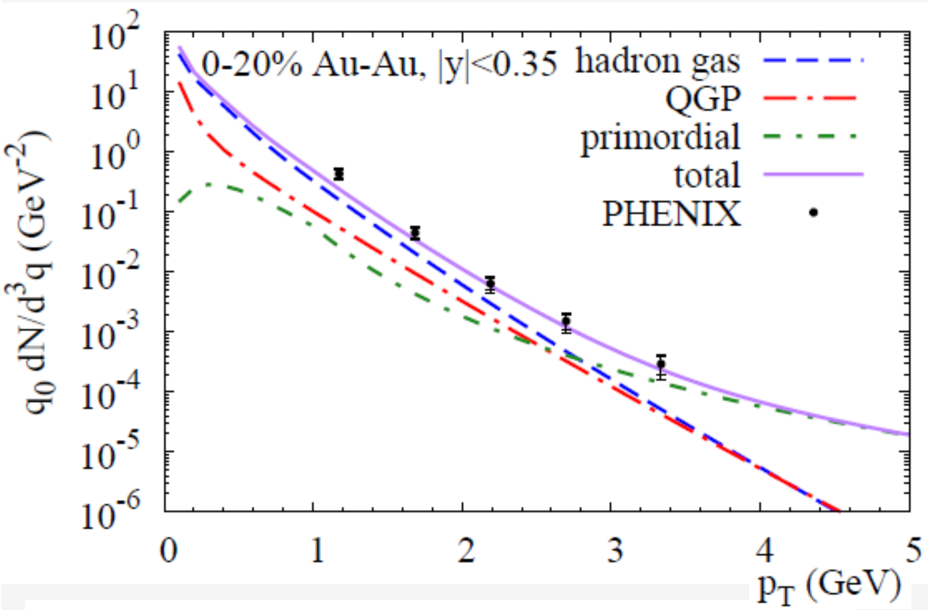
Fireball Evolution

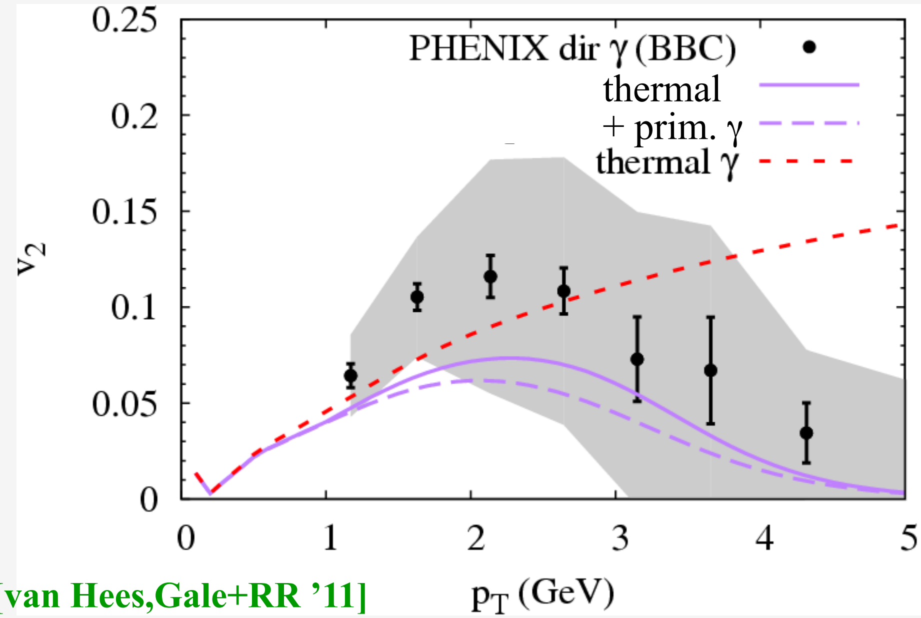


- multi-strange hadrons at "T_c"
- v_2^{bulk} fully built up at hadronization
- chemical potentials for **π, K, …**

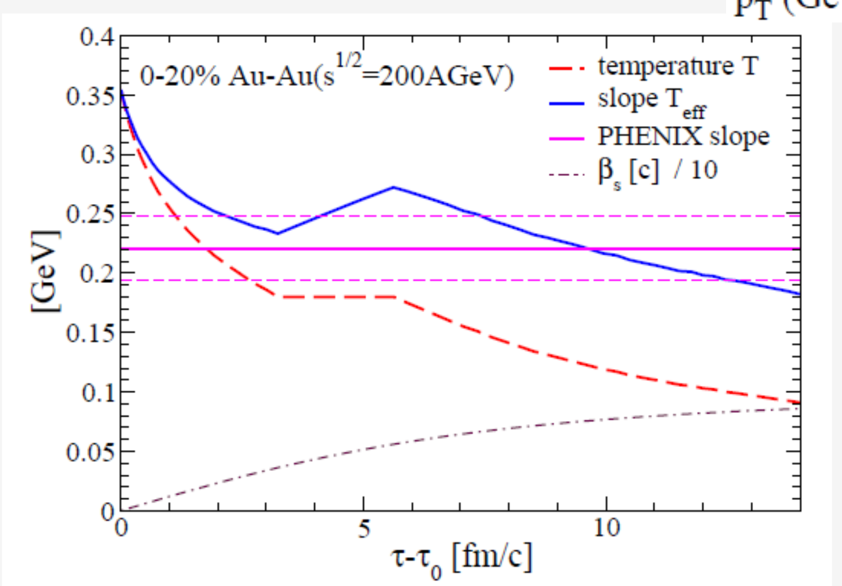
[van Hees et al '11]

4.3.3 Thermal Photon Spectra + v_2: PHENIX



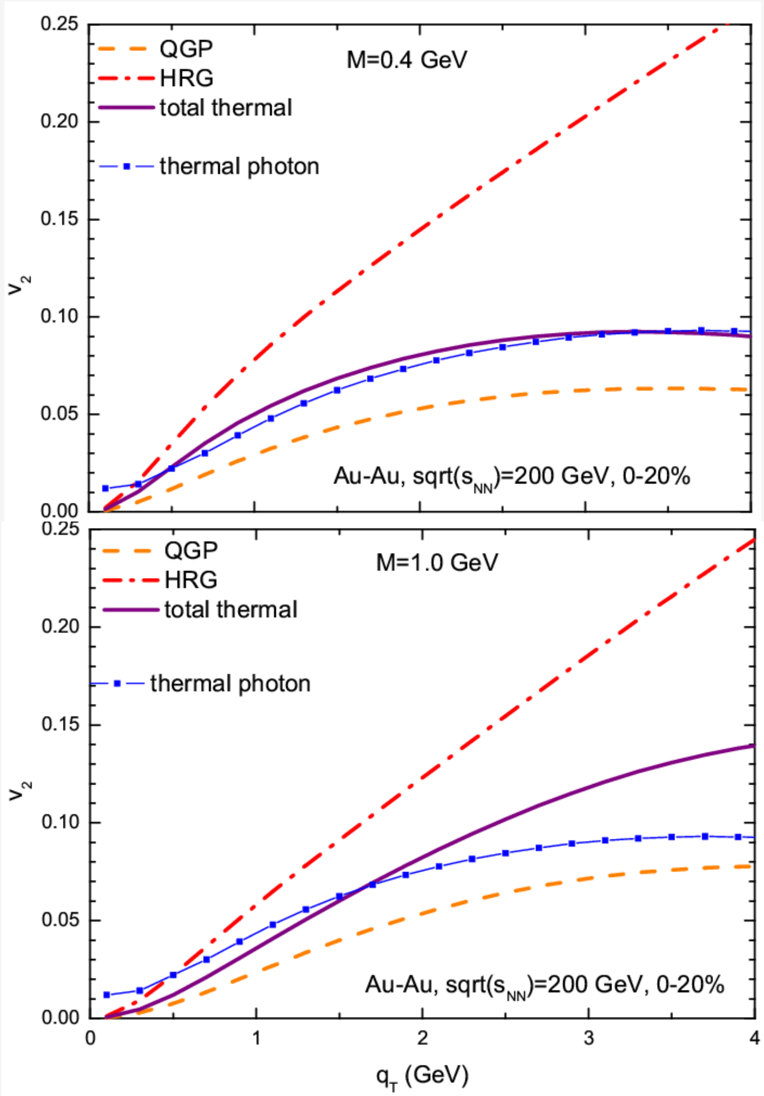


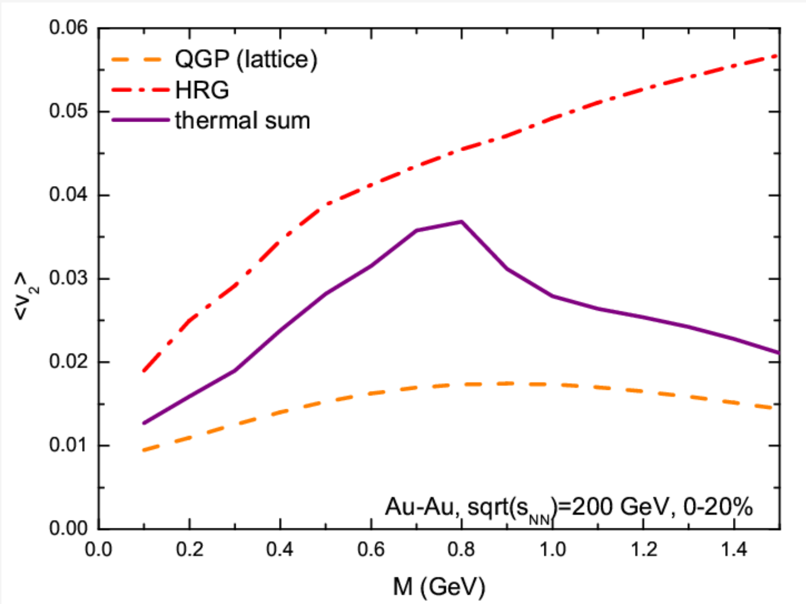
[van Hees,Gale+RR '11]



- "small" slope + large v_2 suggest main emission around T_c
- confirmed within hydro [He at al in prep.]
- exotic mechanisms:
  - glasma BE? [Liao at al '12]
  - $U_A(1)$? [Skokov et al '12]

4.4 Elliptic Flow of Dileptons at RHIC





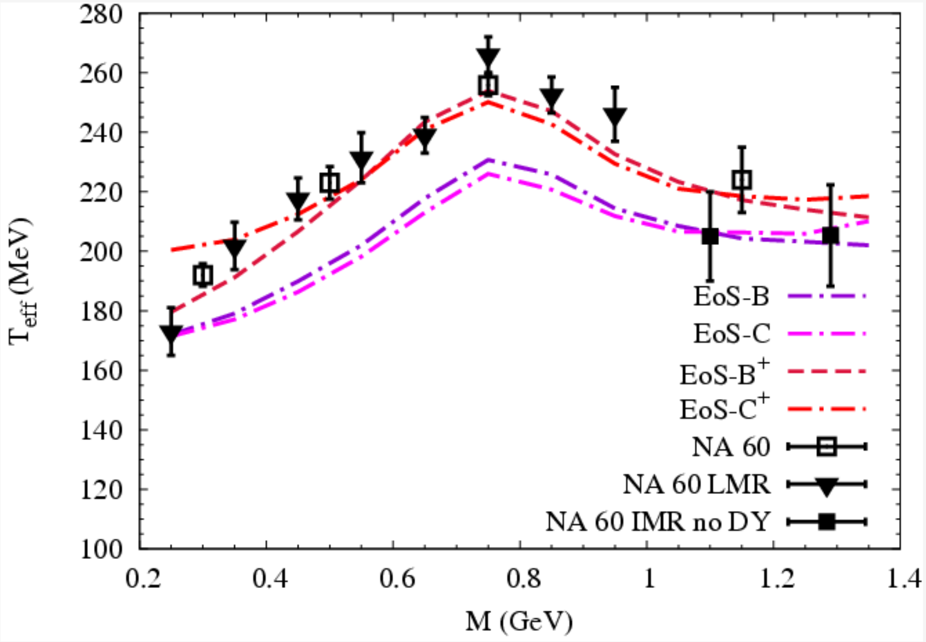
- maximum structure due to late ρ decays

[He et al '12]

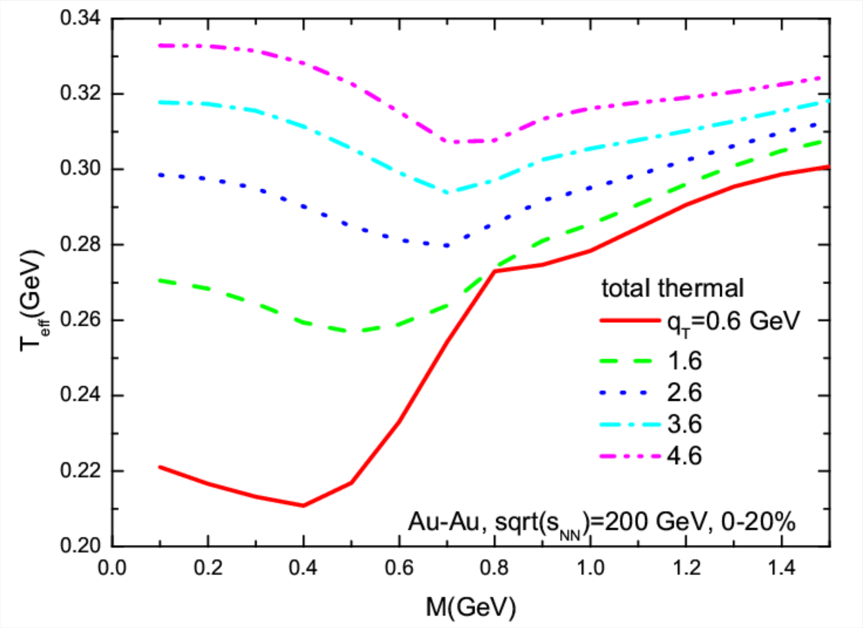
[Chatterjee et al '07, Zhuang et al '09]

4.5 QGP Barometer: Blue Shift vs. Temperature

SPS



RHIC



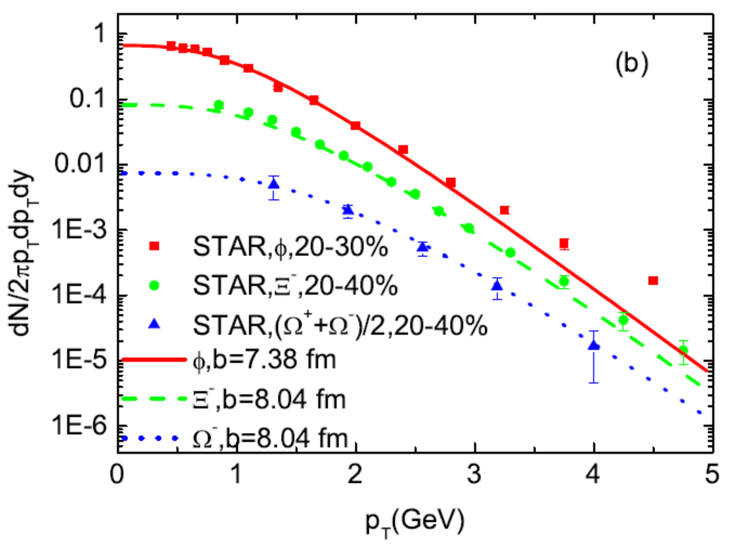
- QGP-flow driven increase of $T_{eff} \sim T + M\,(\beta_{flow})^2$ at **RHIC**
- high p_t: high **T** wins over high-flow ρ's → minimum (opposite to **SPS**!)
- saturates at "true" early temperature T_0 (no flow)

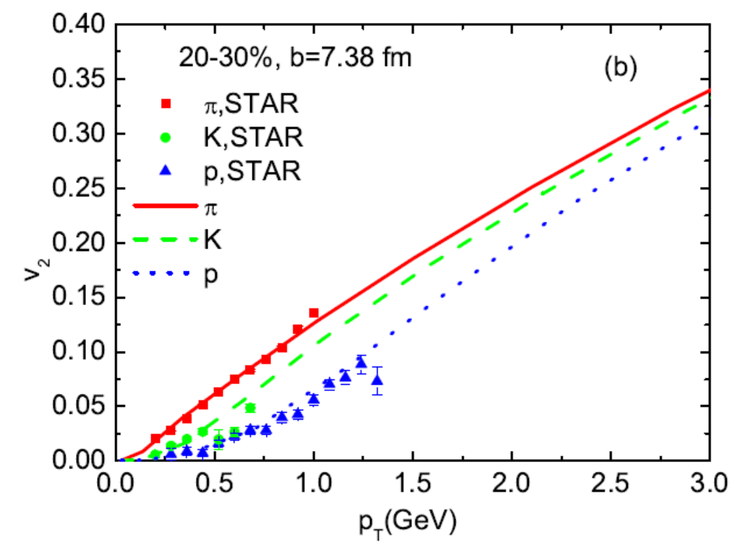
5.) Conclusions

- Axial/Vector spectral functions **well suited** to quantify chiral symmetry breaking and restoration
- **Constraints** on in-medium V/A spectral functions:
  - elementary reactions
  - lattice QCD correlators
  - QCD sum rules (condensates)
- Use **EM spectral function** to connect:
  - dilepton/photon data in URHICs
  - Weinberg sum rules
- Corrolary use of EM probes:
  - fireball lifetime + temperature (M-spectra)
  - collectivity to determine emission source
- **Interpretation of RHIC results wide open**

4.1 Quantitative Bulk-Medium Evolution

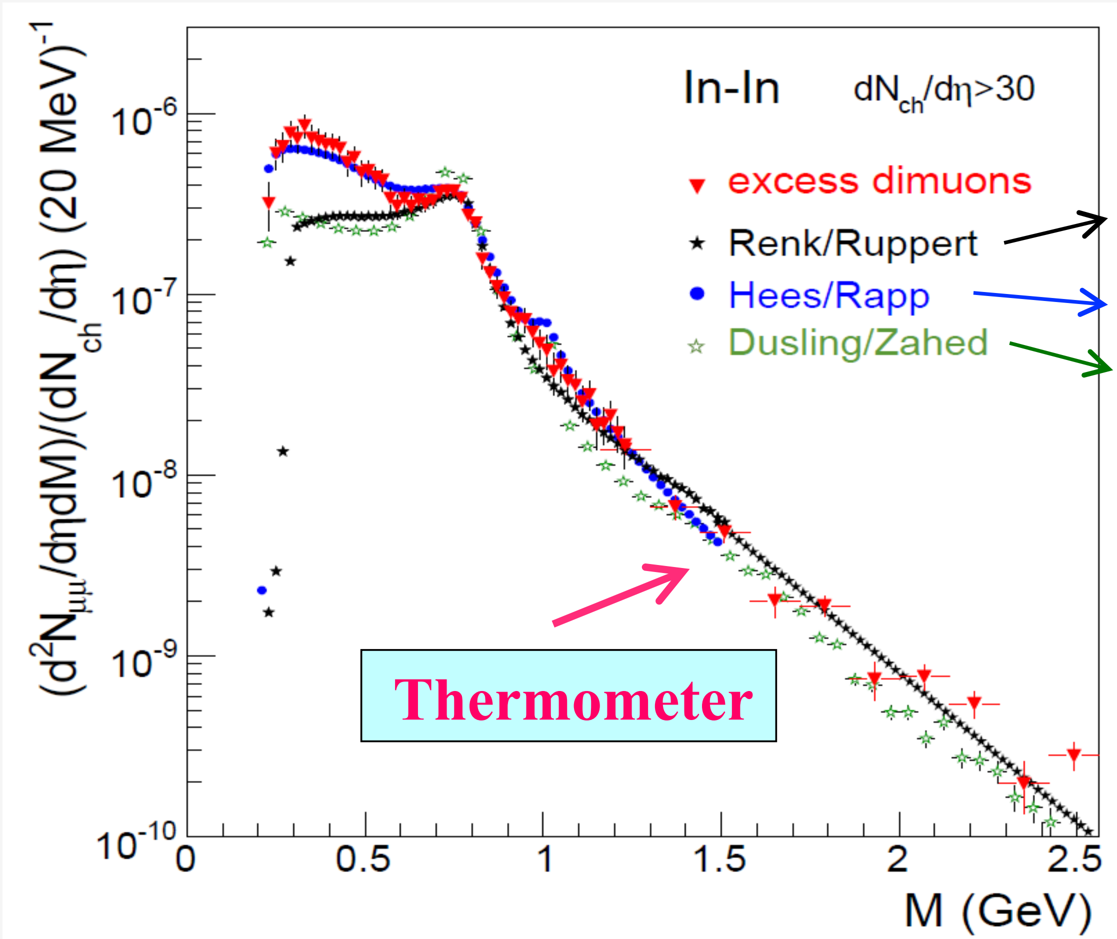
- initial conditions (compact, initial flow?)
- EoS: lattice (QGP, T_c~170MeV) + chemically frozen hadronic phase
- spectra + elliptic flow: multistrange at T_{ch} ~ 160MeV [He et al '11]
  π, K, p, Λ, … at T_{fo} ~ 110MeV





- v_2 saturates at T_{ch}, good light-/strange-hadron phenomenology

4.1.3 Mass Spectra as Thermometer



Emp. scatt. ampl. + T-ρ approximation

Hadronic many-body

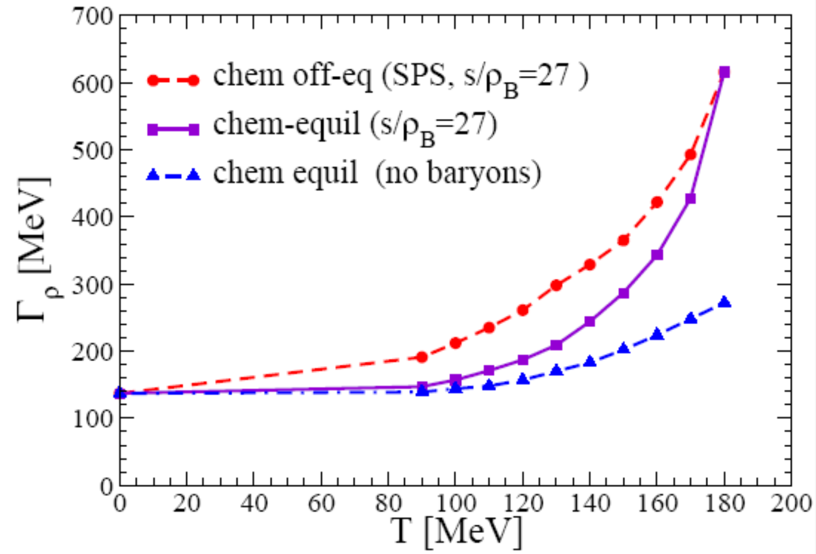
Chiral virial expansion

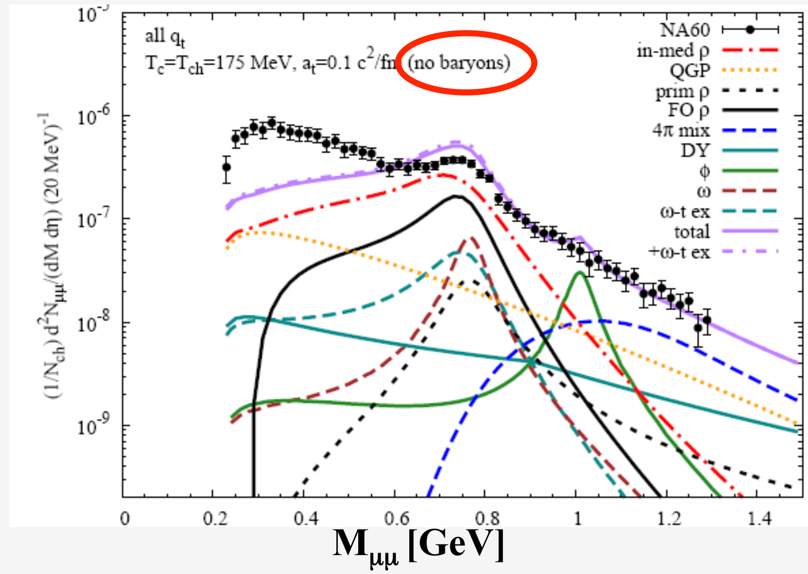
[NA60, CERN Courier Nov. 2009]

- Overall slope T~150-200MeV (true T, no blue shift!)

4.1.2 Sensitivity to Spectral Function

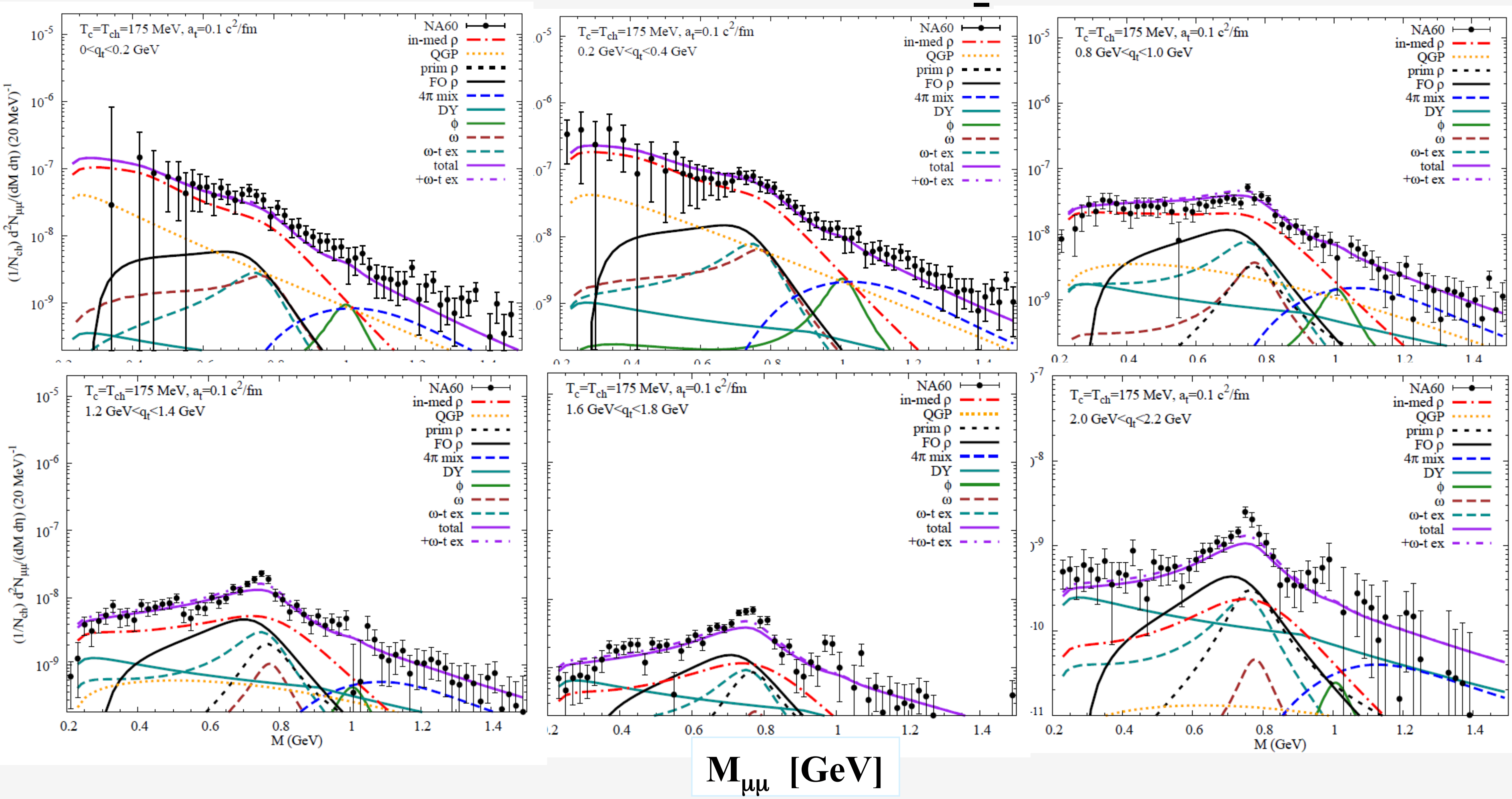
In-Medium ρ-Meson Width





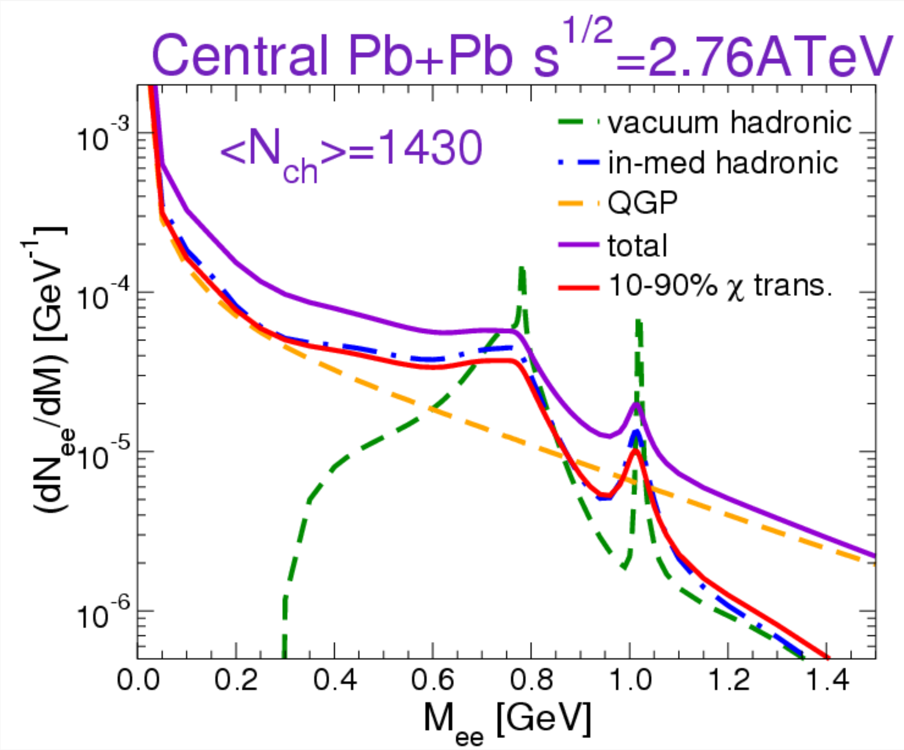
- avg. Γ_ρ(T~150MeV)~370 MeV $\Rightarrow$ Γ_ρ (T~T$_c$) ≈ 600 MeV $\rightarrow$ m_ρ
- driven by (anti-) baryons

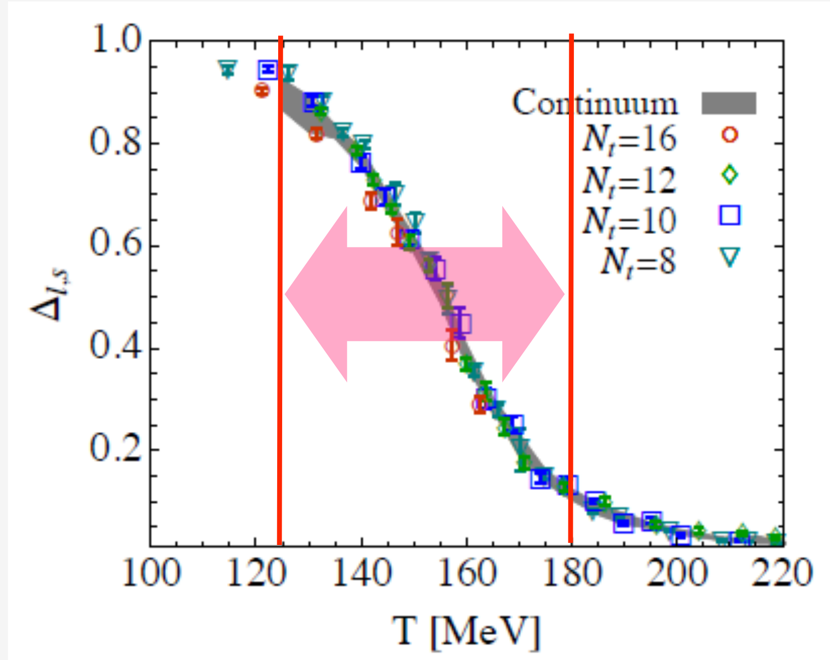
2.3.2 NA60 Mass Spectra: p_t Dependence



- more involved at **p_T>1.5GeV**: Drell-Yan, primordial/freezeout ρ , …

5.2 Chiral Restoration Window at LHC





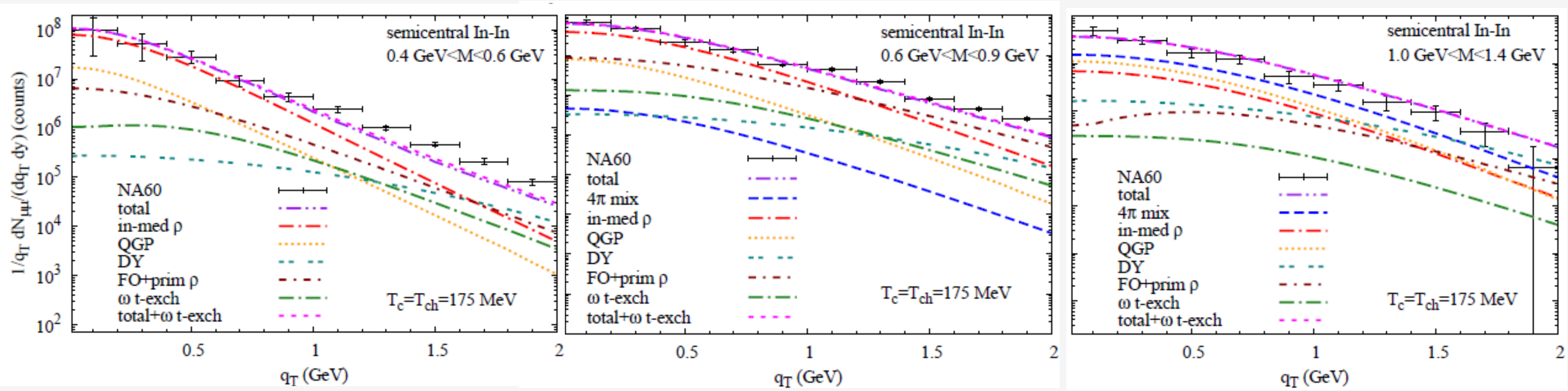
- low-mass spectral shape in chiral restoration window:

  ~60% of thermal low-mass yield in "chiral transition region"

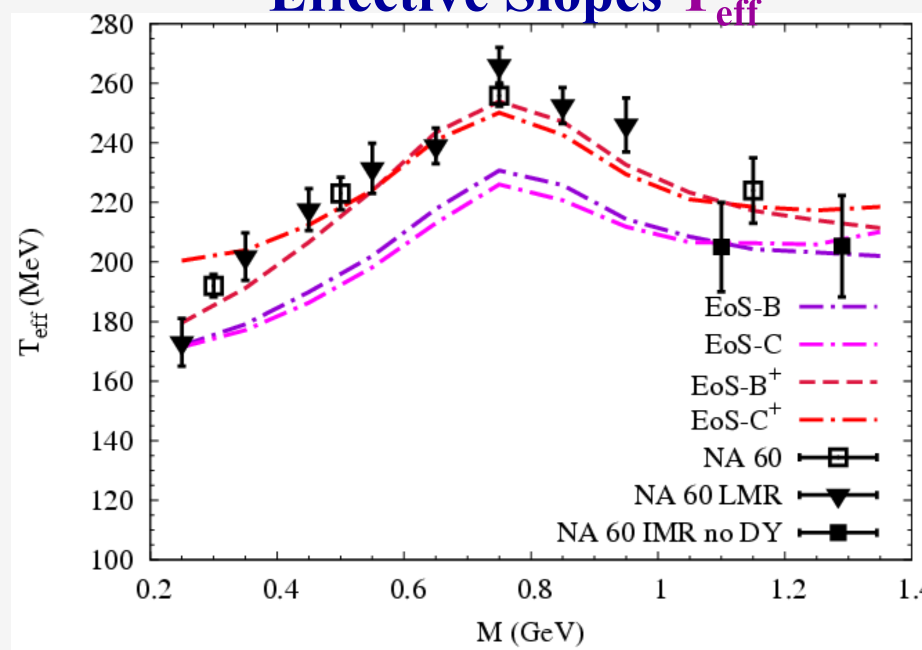
  (T=125-180MeV)

- enrich with (low-) $\mathbf{p_t}$ cuts

4.3 Dimuon p_t-Spectra and Slopes: Barometer



Effective Slopes T_{eff}



- theo. slopes originally too soft
- increase fireball acceleration,
  e.g. $a_\perp$ = 0.085/fm → 0.1/fm
- insensitive to T_c=160-190MeV

Outline

2.) Chiral Symmetry Breaking in Vacuum

- "Higgs Mechanism", Condensates + Mass Gap in QCD
- Hadron Spectrum, Chiral Partners + Sum Rules

3.) EM Spectral Function in Medium

- Hadronic Theory
- QGP + Lattice QCD

4.) Highlights of EM Probes in Heavy-Ion Collisions

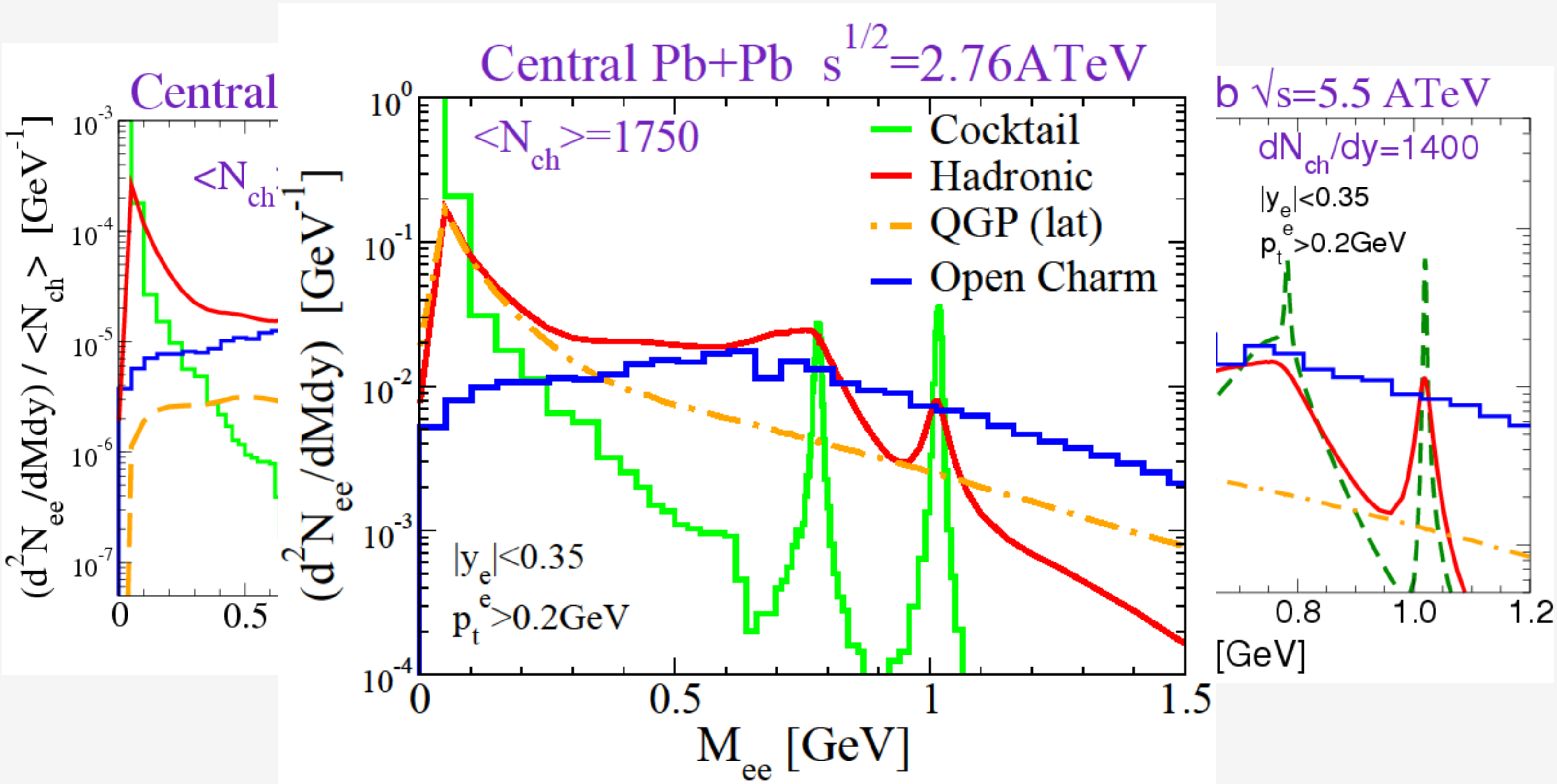
- Spectro-, Thermo-, Chrono- + Baro-meter
- Thermal Photons

5.) Low-Mass Dileptons at LHC

- Mass Spectra + Collectivity

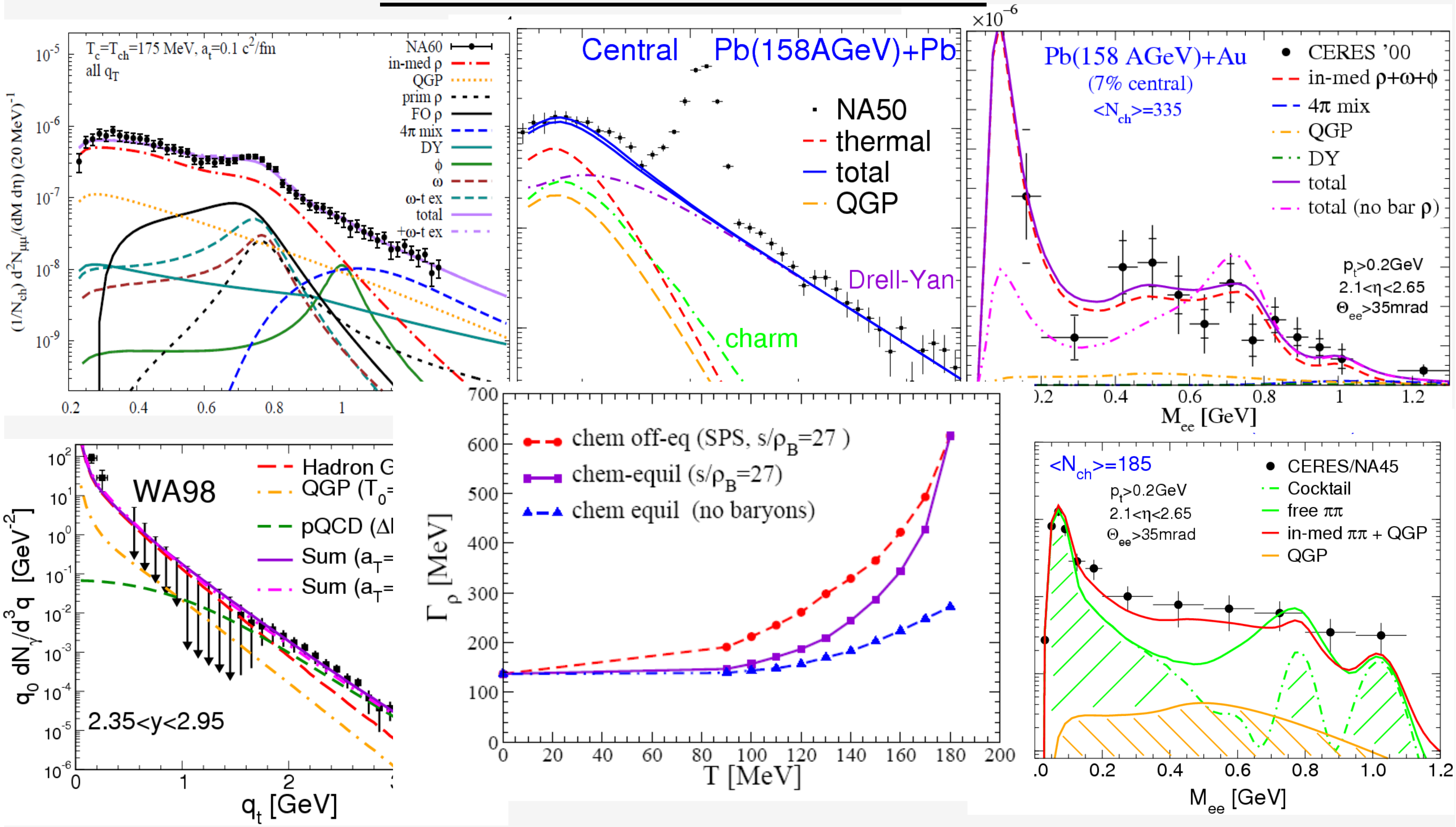
6.) Conclusions

5.1 Thermal Dileptons at LHC



- charm comparable, accurate (in-medium) measurement critical
- low-mass spectral shape in chiral restoration window

2.2 EM Probes at SPS



• all calculated with the **same e.m. spectral function**!

•thermal source: **T_i≈210MeV**, HG-dominated, **ρ-meson melting**!

2.) Transport: Electric Conductivity

$$\sigma_{\rm em} = -e^2 \lim_{q_0 \to 0} \frac{\partial}{\partial q_0} Im\Pi_{\rm em}(q_0, q=0) = -e^2 \lim_{q_0 \to 0} \frac{1}{q_0} Im\Pi_{\rm em}(q_0, q=0)$$

- hadronic theories (T~150MeV):
  - chiral pert. theory (pion gas): $\sigma_{em} / T \sim 0.11\ e^2$ [Fernandez-Fraile+ Gomez-Nicola '07]
  - hadronic many-body theory: $\sigma_{em} / T \sim 0.09\ e^2$

- lattice QCD ($T \sim (1.5\text{-}3)\ T_c$): [Gupta '04, Aarts et al '07, Ding et al. '11]
  $\sigma_{em} / T \sim (0.26 \pm 0.02)\ e^2$

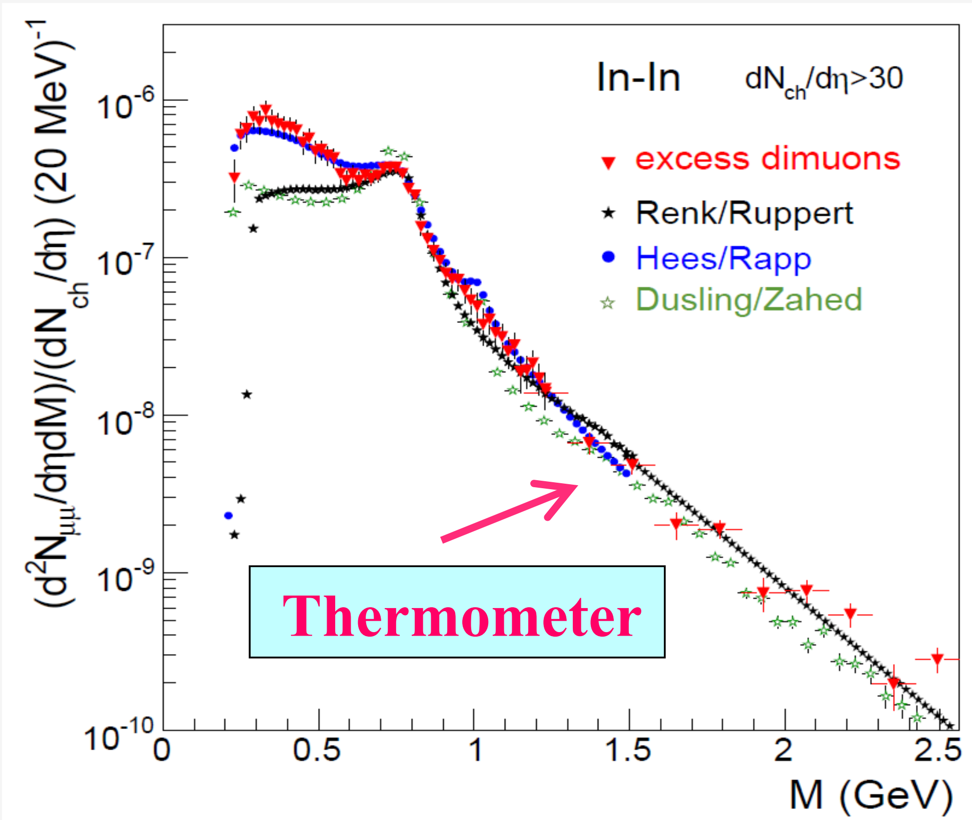
- soft-photon limit of thermal emission rate

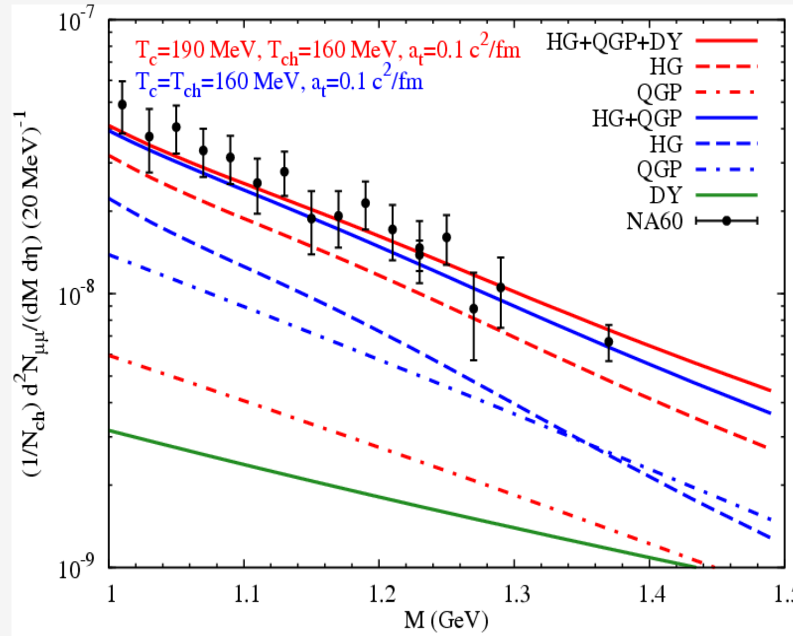
$$q_0 \frac{dN_\gamma}{d^4x d^3q}(q_0 \to 0) = \frac{T}{4\pi^3} \sigma_{\rm em}$$

- **EM Susceptibility** (→ charge fluctuations):
  $\langle Q^2 \rangle - \langle Q \rangle^2 = \chi_{em} = \Pi_{em}(q_0=0, q \to 0)$

5.2 Intermediate-Mass Dileptons: Thermometer

• use **invariant** continuum radiation (**M>1GeV**): no blue shift, **T_{slope}** =

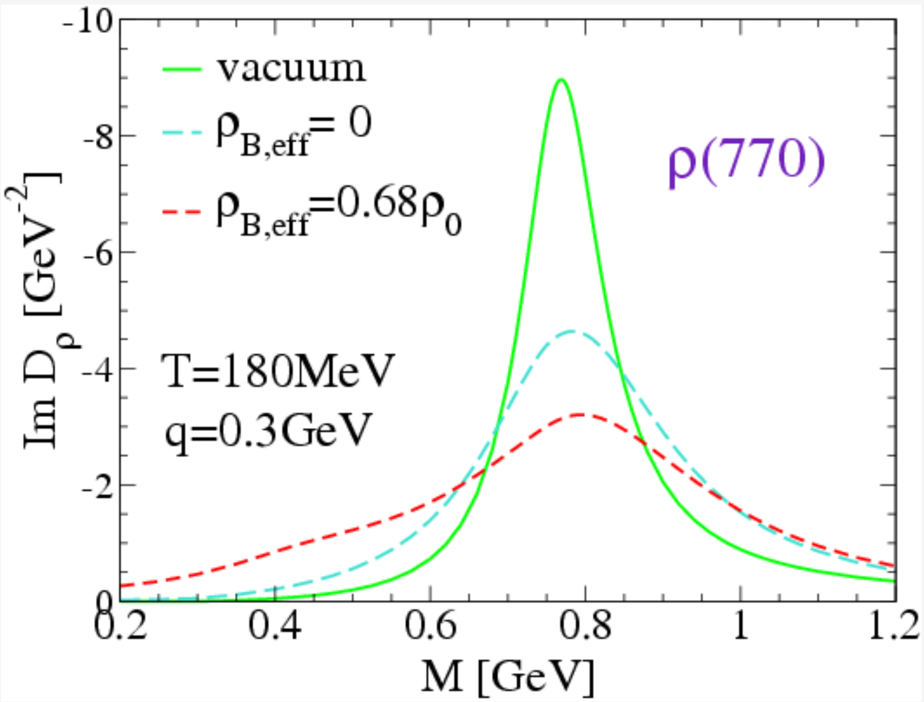


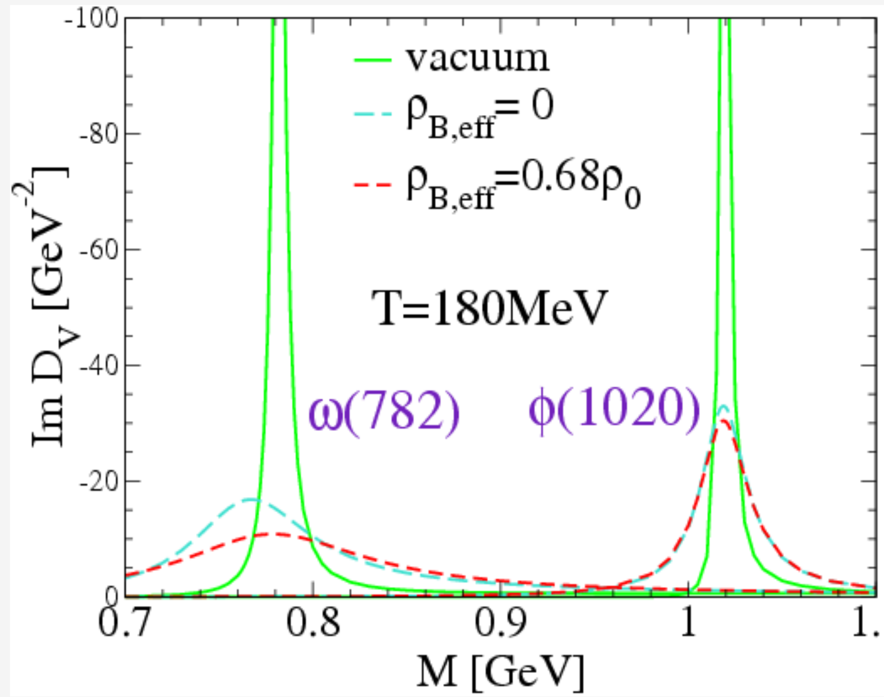


• independent of partition HG vs QGP (dilepton rate continuous/dual)

• initial temperature **T_i ~ 190-220 MeV** at **CERN-SPS**

4.7.2 Light Vector Mesons at RHIC + LHC



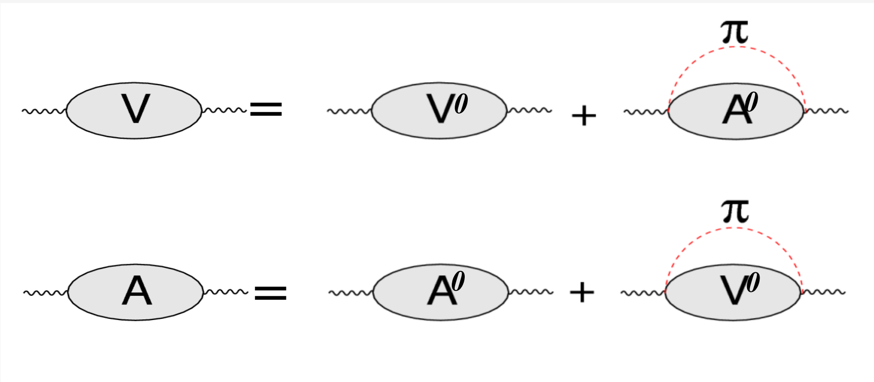


- **baryon effects important even at $\rho_{B,tot}= 0$:**
  sensitive to $\rho_{Btot}= \rho_B + \rho_B$ (ρ-N and ρ-N̄ interactions identical)
- **ω also melts, ϕ more robust ↔ OZI**

5.3 Intermediate Mass Emission: "Chiral Mixing"

[Dey, Eletsky +Ioffe '90]

- low-energy pion interactions fixed by chiral symmetry



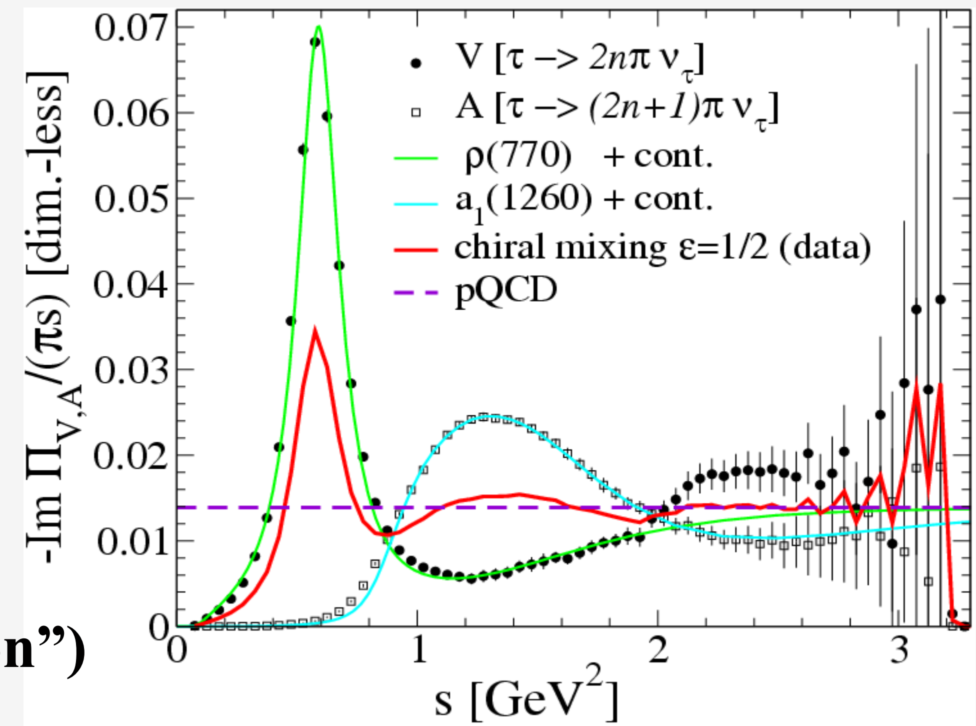
$$\Pi_V^{\mu\nu}(q) = (1-\varepsilon)\,\Pi_V^{0,\mu\nu}(q) + \varepsilon\,\Pi_A^{0,\mu\nu}(q)$$

$$\Pi_A^{\mu\nu}(q) = (1-\varepsilon)\,\Pi_A^{0,\mu\nu}(q) + \varepsilon\,\Pi_V^{0,\mu\nu}(q)$$

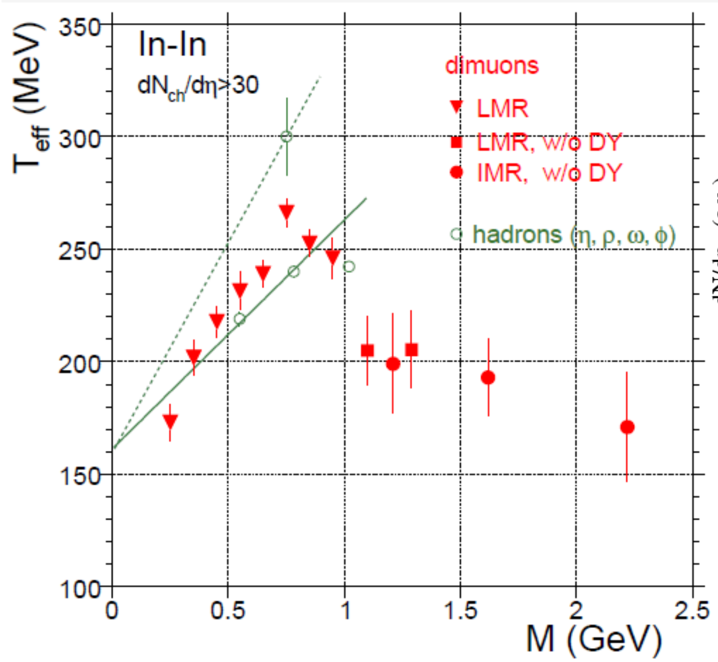
- mixing parameter

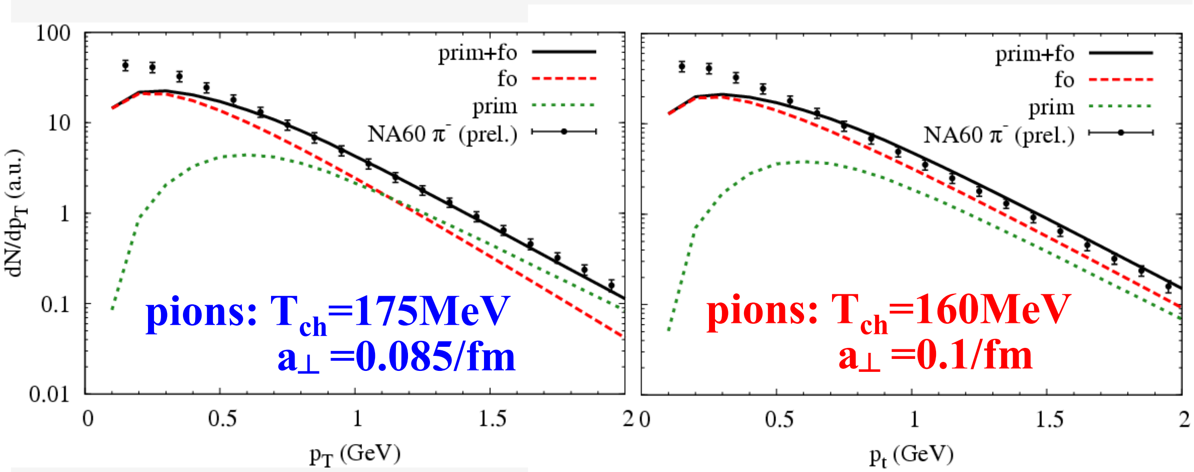
$$\varepsilon = \frac{4}{f_\pi^2}\int \frac{d^3k}{(2\pi)^3 2\omega_k}\, f^\pi(\omega_k) \approx \frac{T^2}{6 f_\pi^2}$$

- **degeneracy with perturbative spectral fct. down to M~1GeV**
- physical processes at M≥ 1GeV: **$\pi a_1 \rightarrow e^+e^-$ etc. ("4π annihilation")**

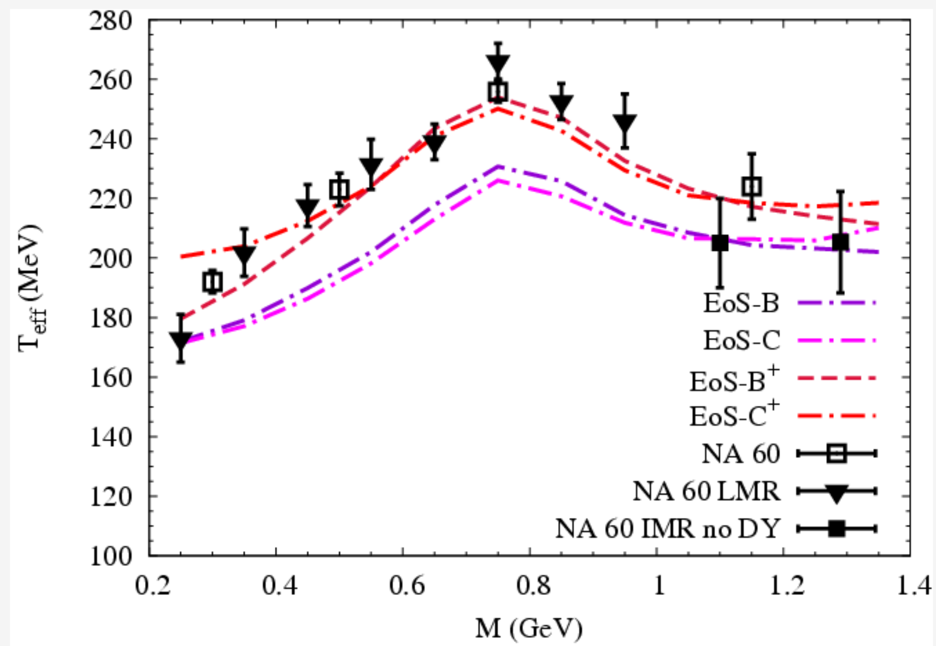


3.2 Dimuon p_t-Spectra and Slopes: Barometer





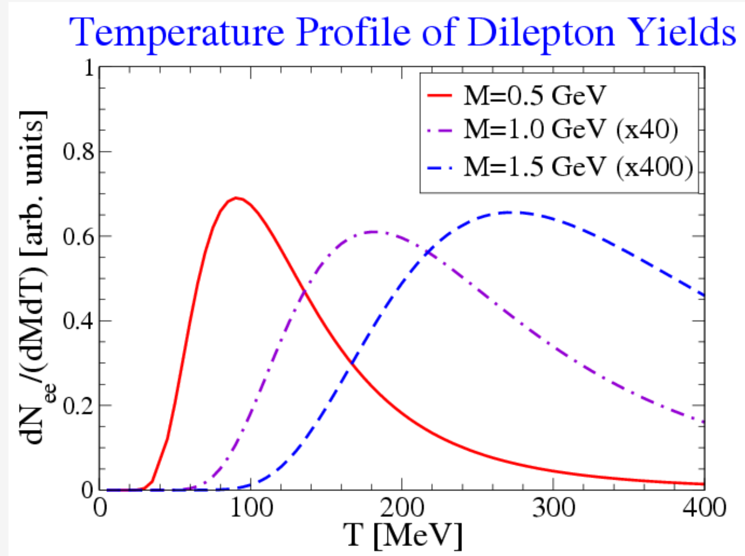
- modify fireball evolution:
  e.g. **$a_\perp = 0.085/\mathrm{fm} \rightarrow 0.1/\mathrm{fm}$**
- both large and small T_c compatible with excess dilepton slopes



4.4.3 Origin of the Low-Mass Excess in PHENIX?

- **QGP radiation insufficient:**

  space-time , lattice QGP rate + resum. pert. rates **too small**



- **must be of long-lived hadronic origin**

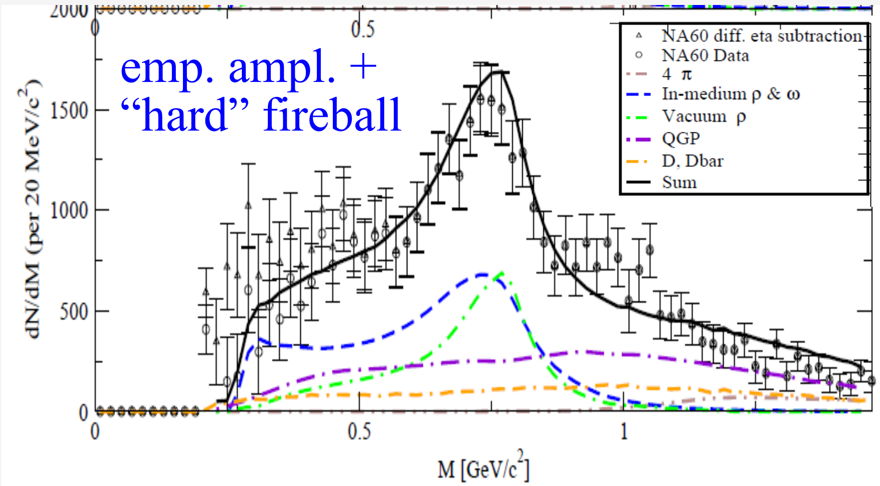
- **Disoriented Chiral Condensate (DCC)?** **[Bjorken et al '93, Rajagopal+Wilczek '93]**
  - "baked Alaska" $\leftrightarrow$ small **T**
  - rapid quench+large domains $\leftrightarrow$ central **A-A**
  - $\pi_{therm} + \pi_{DCC} \rightarrow e^+e^-$ $\leftrightarrow$ **M~0.3GeV**, small p_t

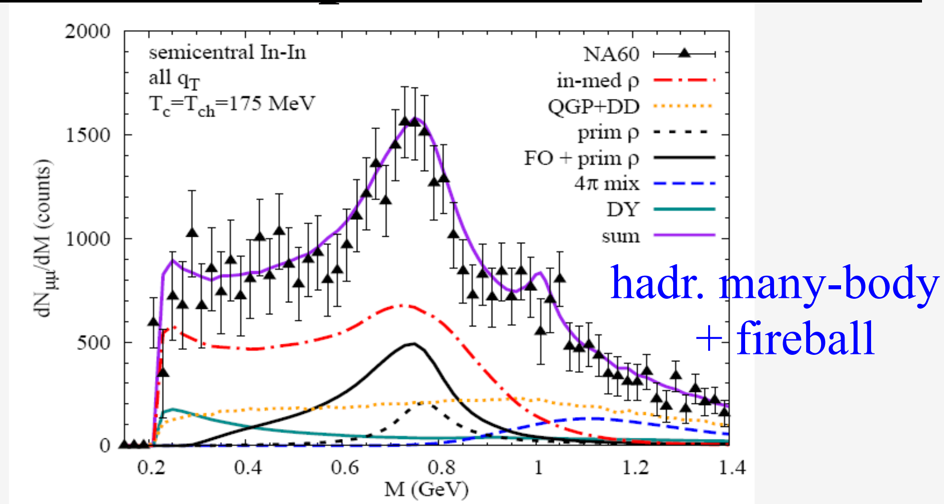
  [Z.Huang+X.N.Wang '96 Kluger,Koch,Randrup '98]

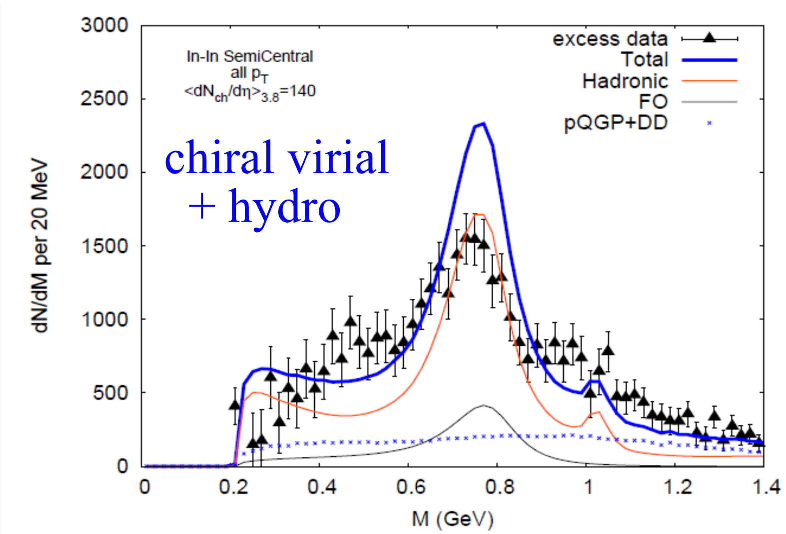
- **Lumps of self-bound pion liquid?**

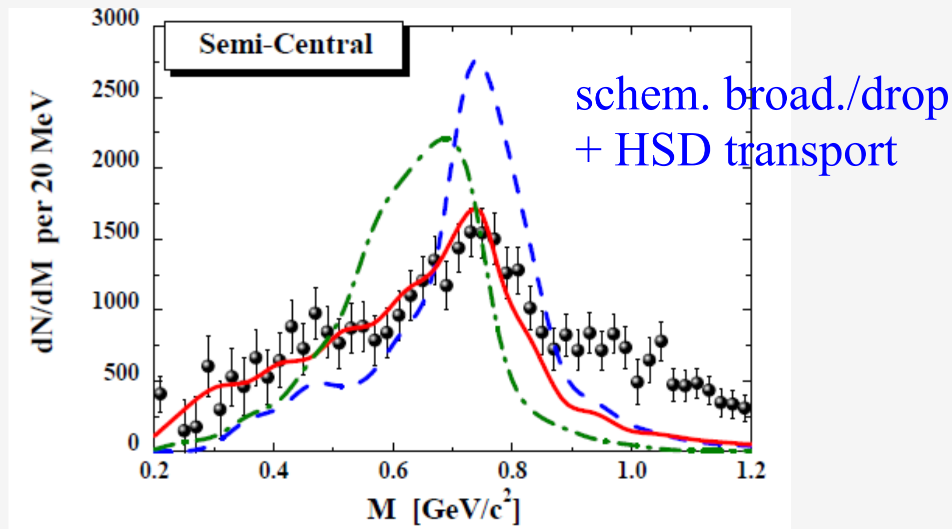
- **Challenge: consistency with hadronic data, NA60 spectra!**

2.3.3 Spectrometer III: Before Acceptance Correction





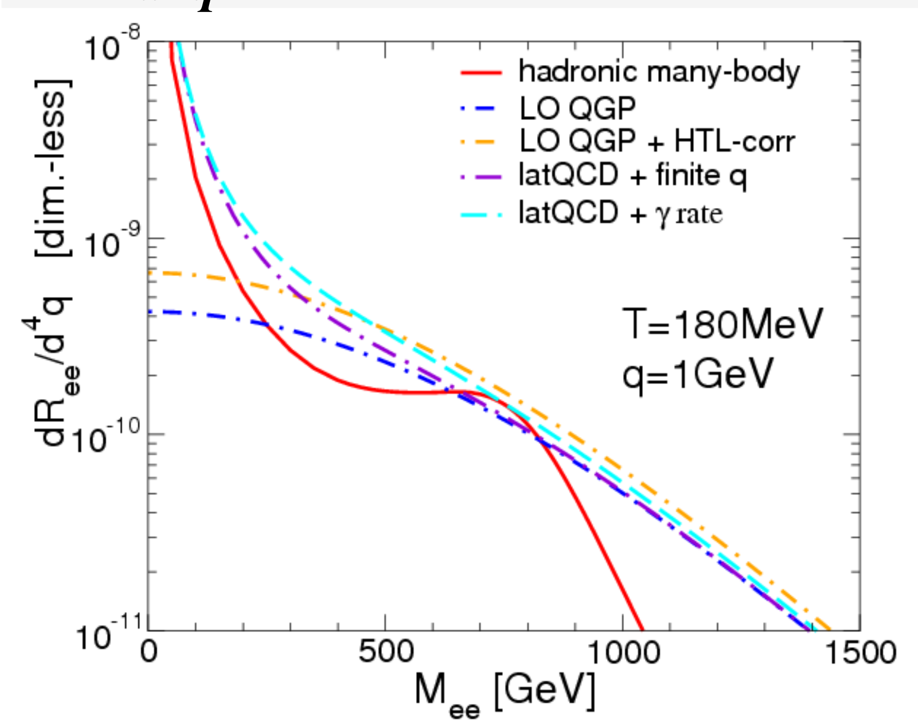


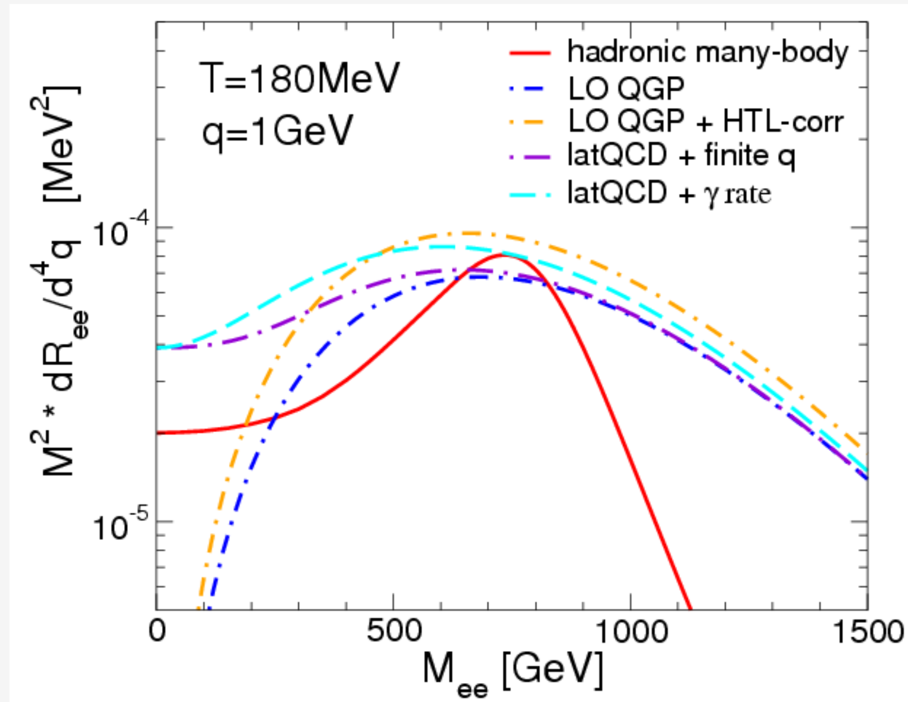


- **Discrimination power much reduced**
- can compensate spectral “deficit” by larger flow: lift pairs into acceptance

4.2 Improved Low-Mass QGP Emission

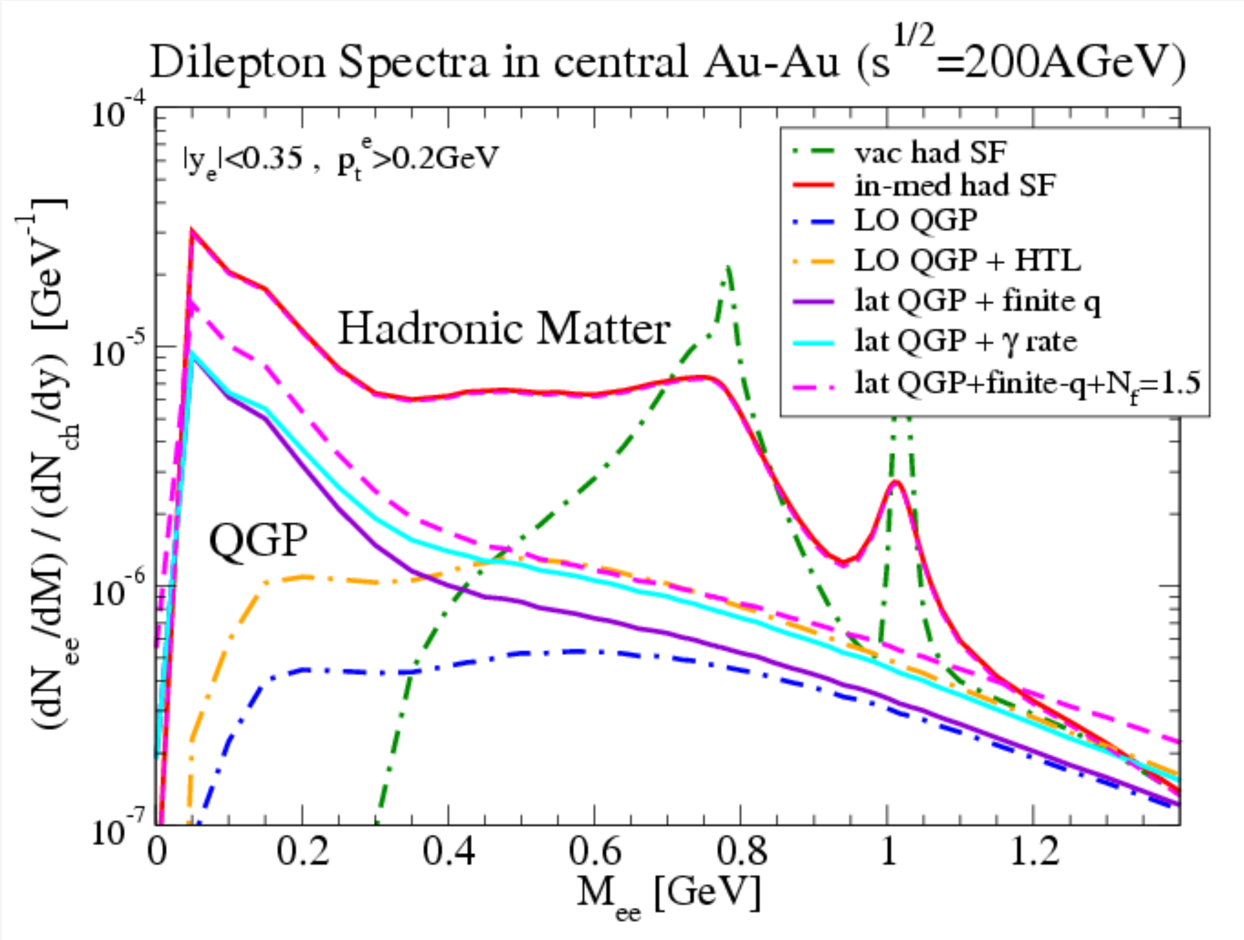
$$\frac{dR_{ee}}{d^4q} = \frac{\alpha_{em}^2}{6\pi^3 M^2} f^B(q_0;T)\,\rho_V(q_0,q)$$





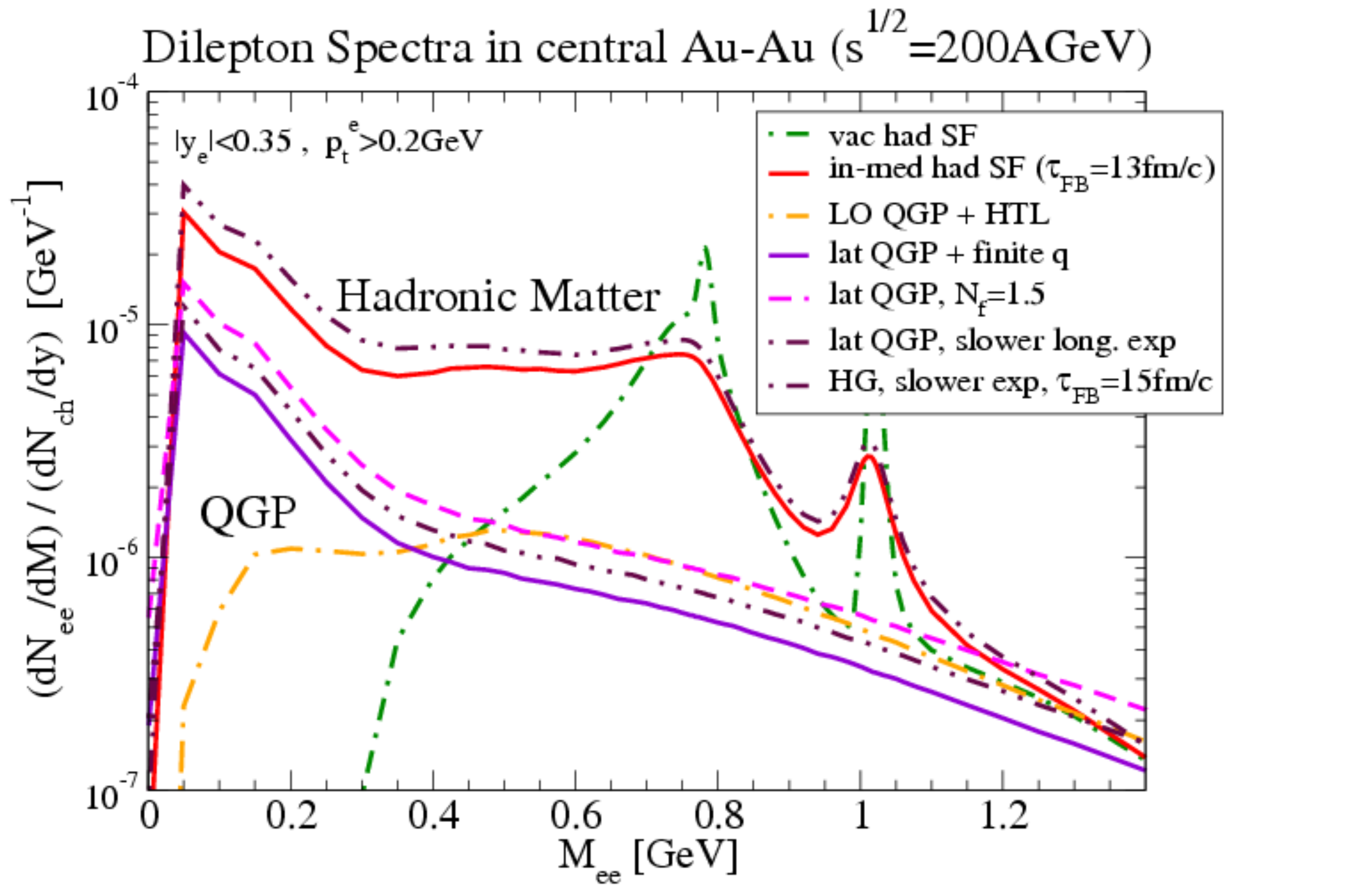
- LO pQCD spectral function: $\rho_V(q_0,q) = \frac{6}{9}\, 3M^2/2\pi\,[1+Q_{HTL}(q_0)]$
- 3-momentum augmented lattice-QCD rate (finite γ rate)

4.4.1 Variations in QGP Radiation



- improvements in QGP rate insufficient

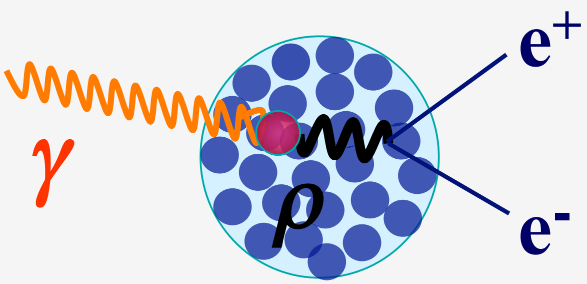
4.4.2 Variations in Fireball Properties

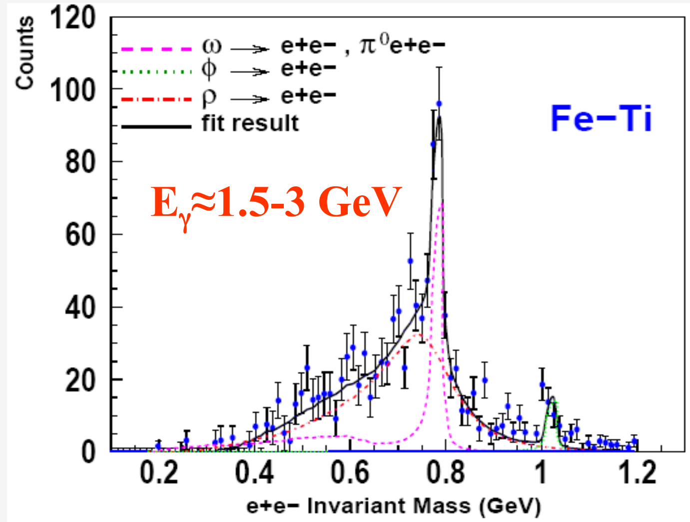


- variations in space-time evolution only significant in (late) hadronic phase

4.1 Nuclear Photoproduction: ρ Meson in Cold Matter

$\gamma + A \rightarrow e^+e^- X$



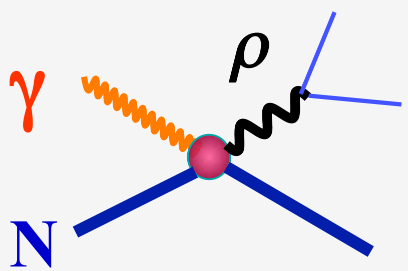


- extracted "in-med" ρ-width $\Gamma_\rho \approx 220$ MeV

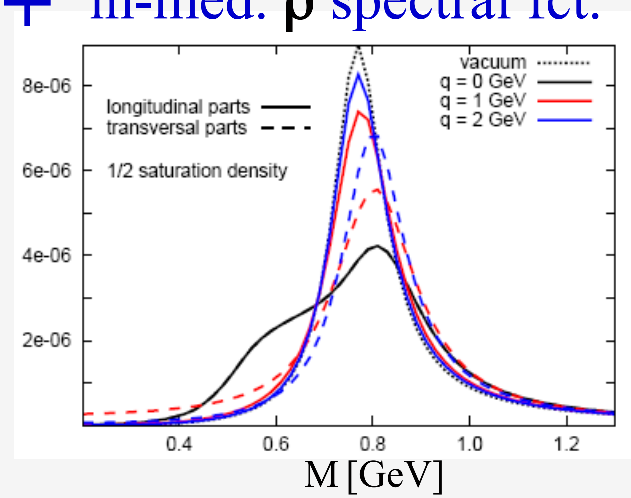
[CLAS+GiBUU '08]

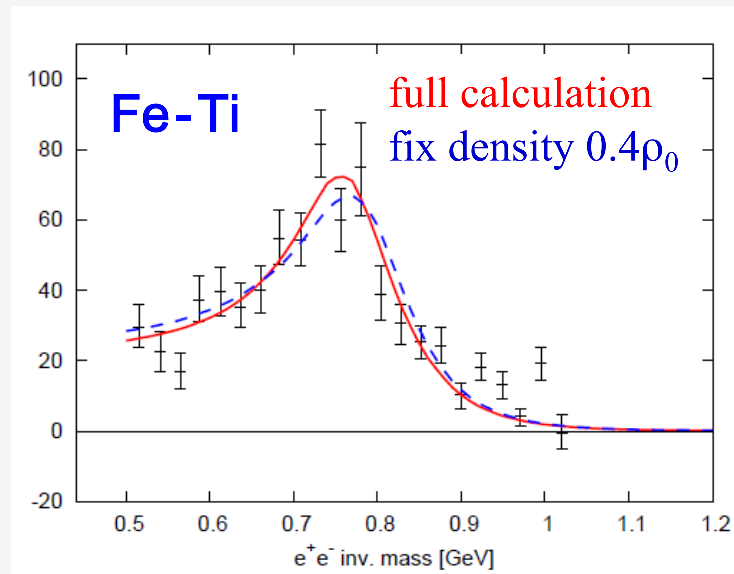
- **Microscopic Approach:**

product. amplitude + in-med. ρ spectral fct.



[Riek et al '08, '10]

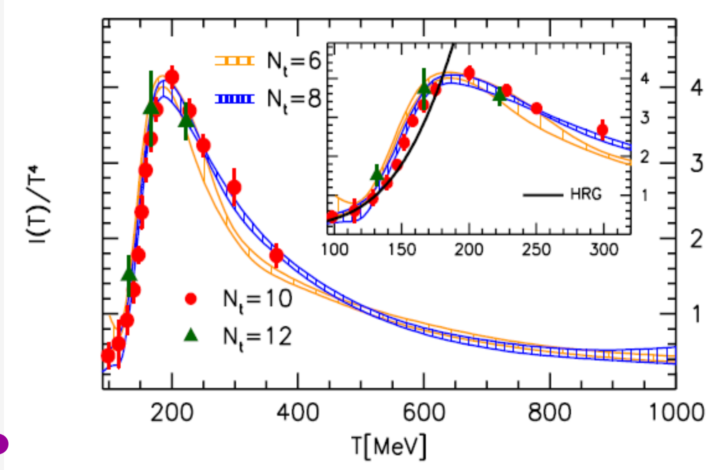




- ρ-broadening reduced at high 3-momentum; **need low momentum cut!**

1.2 Intro-II: EoS and Particle Content

- **Hadron Resonance Gas until close to T_c**
  - **but** far from non-interacting:
    short-lived resonances **R**:
    a + b → R → a + b , $\tau_R \leq 1$ fm/c

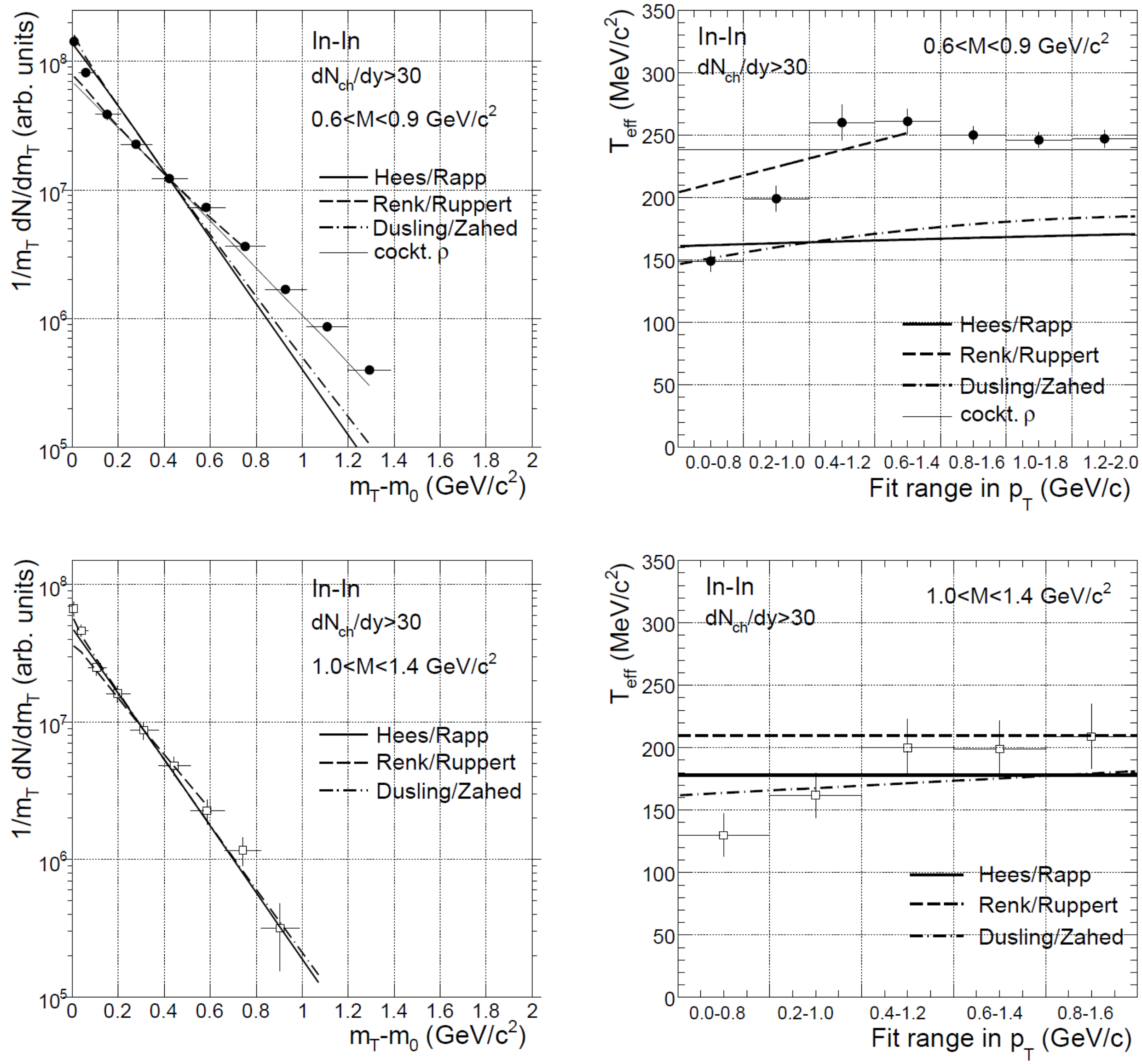


- **Parton Quasi-Particles shortly above T_c**
  - **but** large interaction measure **$I(T) = \varepsilon - 3P$**

⇒ **both "phases" strongly coupled (hydro!):**

- large interaction rates → large collisional widths
- resonance broadening → melting → quarks
- broad parton quasi-particles
- "Feshbach" resonances around T_c **(coalescence!)**

2.3.6 Hydrodynamics vs. Fireball Expansion



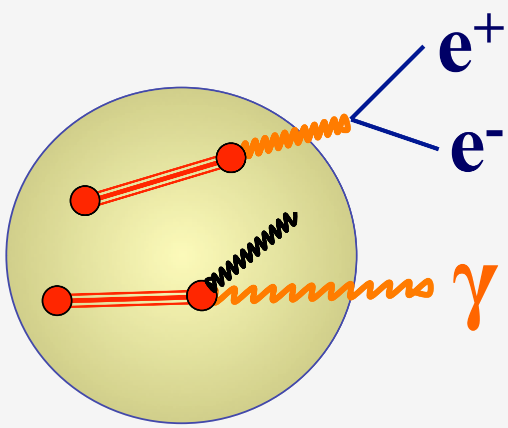
- very good agreement between original hydro [Dusling/Zahed] and fireball [Hees/Rapp]

2.1 Thermal Electromagnetic Emission

EM Current-Current Correlation Function:

$$\Pi^{\mu\nu}_{\rm em}(q) = -i \int d^4x \, e^{iqx} \, \Theta(x_0) \, \langle [\, j^{\mu}_{\rm em}(x), j^{\nu}_{\rm em}(0)] \rangle_T$$

Thermal Dilepton and Photon Production Rates:



$$\frac{dR_{ee}}{d^4q} = \frac{-\alpha^2_{\rm em}}{\pi^3 M^2} f^B(T) \; Im\,\Pi_{\rm em}(M,q)$$

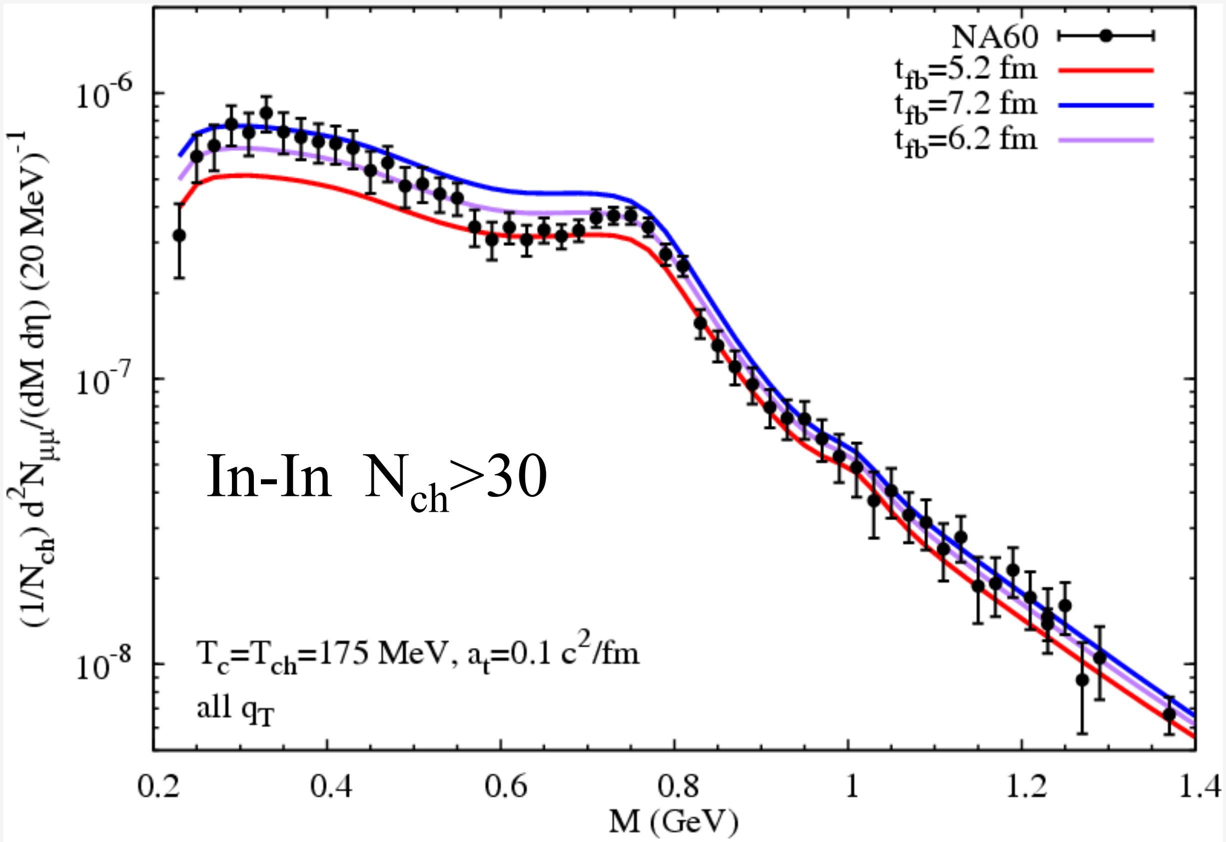
$$q_0 \frac{dR_\gamma}{d^3q} = \frac{-\alpha_{\rm em}}{\pi^2} f^B(T) \; Im\,\Pi_{\rm em}(q_0{=}q)$$

Low Mass:

$$Im\Pi_{\rm em} \sim [ImD_\rho + ImD_\omega/10 + ImD_\phi/5]$$

ρ-meson dominated

4.2 Low-Mass Dileptons: Chronometer



- first "explicit" measurement of interacting-fireball **lifetime**:
  $\tau_{FB} \approx (7\pm1)$ fm/c